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Monitoring Completed Navigation Projects (MCNP) Program

User's Manual for Armor Stone Evaluation Model (ARMOR)

Great Lakes Armor Stone Study

Mansour Zakikhani, Danny W. Harrelson, Amber L. Tillotson, and John D. Ables

August 2015

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Mansour Zakikhani

Environmental Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Danny W. Harrelson, Amber L. Tillotson, and John D. Ables

Geotechnical and Structures Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Final report

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Under Monitoring Completed Navigation Projects (MCNP) Program
Great Lakes Armor Stone Rapid Deterioration work unit

Abstract

Protecting entrances to navigation channels or other coastal areas requires evaluating maritime structures that often feature a surface layer of armor stones, such as rubble-mound breakwaters and jetties. Armor rocks are impacted by natural elements such as seasonal weather and repeated cycles of temperature, flowing water, wetting and drying, wave action, and freeze and thaw. The Armor Stone Evaluation (ARMOR) numerical simulation model consists of stone deterioration software developed to integrate field observations with numerical tools, and it provides an assessment of stone performance during the life of the rubble-mound structures.

The ARMOR software has several numerical models that predict degradation as rocks are impacted by nature. The software includes a statistical technique (homogeneity index) to characterize rock heterogeneity. Two numerical approaches have been developed to calculate freeze-thaw cycles using long-term site weather data. The software also provides a model to estimate armor weight and thickness, minimum crest width, and number of armor units per unit of area. The calculation uses varying values for the seaward slope and wave height by application of the Hudson formula for rubble-mound structure stability. The degradation model relates laboratory results to modification of mass distribution and reduction at the project site. This report provides instructions for creating input data and running different options of the program.

ARMOR software is distributed on CD or DVD and may be obtained from Dr. Mansour Zakikhani, U.S. Army Engineer Research and Development Center, Environmental Laboratory, 3909 Halls Ferry Road, Vicksburg, MS, 39180; (Mansour.zakikhani@usace.army.mil); phone 601-634-3806.

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Preface

The study reported herein was conducted by the U.S. Army Corps of Engineers (USACE), Engineer Research and Development Center (ERDC), Geotechnical and Structures Laboratory (GSL), as part of the USACE Monitoring Completed Navigation Projects (MCNP) Program (one of the USACE Navigation Programs). Overall management of the MCNP Program is provided by Headquarters USACE (HQUSACE), Washington D.C. The ERDC Coastal and Hydraulics Laboratory (CHL) is responsible for technical and data management and support for HQUSACE review and technology transfer. The HQUSACE Program Monitors for the MCNP Program at the time of this study were James E. Walker, former Chief, Navigation Branch (NB), USACE, and Jeffrey A. McKee, present Chief, NB, USACE. W. Jeff Lillycrop was the ERDC Technical Director for Navigation. MCNP Program Manager during the conduct of this study was Dr. Lyndell Z. Hales, Technical Programs Office, ERDC, CHL.

This report documents the theoretical basis and provides instructions for use of the Armor Stone Evaluation (ARMOR) numerical simulation model developed by ERDC GSL and Environmental Laboratory (EL). The code integrates results of other project tasks that have been performed by ERDC in collaboration with U.S. Army Corps of Engineer Districts Buffalo (LRB), Detroit (LRE), and Chicago (LRC).

Dr. Mansour Zakikhani, Environmental Modeling Branch (EMB), Environmental Processes and Engineering Division (EPED), EL, and Danny W. Harrelson, Geotechnical Engineering and Geosciences Branch (GEGB), Geosciences and Structures Division (GSD), GSL, conducted the study. Appreciation is extended to Mike K. Allis, LRE, and Shanon Chader, LRB, who provided technical review of ARMOR software and critically reviewed this technical report.

This report was prepared by Dr. Mansour Zakikhani (EL); and Danny W. Harrelson, Amber Tillotson, and John D. Ables (GSL). The research was accomplished under the general supervision of Dr. Dorothy Tillman, Chief, EMB, EPED, EL; Chad Gartrell, Chief, GEGB, GSD, GSL; Bartley P. Durst, Chief, GSD, GSL; Dr. Jack Davis, Deputy Director, EL; and Dr. Beth Fleming, Director, EL.

LTC John T. Tucker III was Acting Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Permission to publish was granted by Dr. David W. Pittman, former Director, GSL.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
acre-feet	1,233.5	cubic meters
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
degrees (angle)	0.01745329	radians
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
foot-pounds force	1.355818	joules
gallons (US liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
inch-pounds (force)	0.1129848	newton meters
pounds (force) per foot	14.59390	newtons per meter
pounds (force) per inch	175.1268	newtons per meter
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (mass) per cubic inch	2.757990 E+04	kilograms per cubic meter
pounds (mass) per square foot	4.882428	kilograms per square meter
pounds (mass) per square yard	0.542492	kilograms per square meter
slugs	14.59390	kilograms
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
square miles	2.589998 E+06	square meters
square yards	0.8361274	square meters
tons (force)	8,896.443	newtons
tons (2,000 pounds, mass)	907.1847	kilograms
tons (2,000 pounds, mass) per square foot	9,764.856	kilograms per square meter

1 Introduction

1.1 Monitoring Completed Navigation Projects (MCNP) program

The goal of the Monitoring Completed Navigation Projects (MCNP) program, formerly the Monitoring Completed Coastal Projects (MCCP) program, is the advancement of coastal and hydraulic engineering technology with respect to U.S. Army Corps of Engineers (USACE) requirements. The program is designed to determine how well projects are accomplishing their purposes and how well they are resisting attacks by their physical environment. These determinations, combined with concepts and understanding already available, will lead to the creation of more accurate and economical engineering solutions to coastal and hydraulic problems, thus strengthening and improving design criteria and methodology, improving construction practices and cost-effectiveness, and improving USACE Operation and Maintenance (O&M) techniques. Additionally, the monitoring program will identify where current technology is inadequate or where additional research is required.

To develop direction for the program, USACE established an ad hoc committee of engineers and scientists. The committee formulated the objectives of the program, developed its operation philosophy and recommended funding levels, and established criteria and procedures for project selection. A significant result of their efforts was a prioritized listing of problem areas to be addressed or, essentially, a listing of the areas of interest of the program.

USACE offices are invited to nominate projects for inclusion in the monitoring program as funds become available. The MCNP program is governed by Engineer Regulation 1110-2-8151 (Headquarters, USACE (HQUSACE) 1997). A selection committee reviews and prioritizes the nominated projects based on criteria established in the regulation. The prioritized list is reviewed by the program monitors at HQUSACE. Final selection is based on this prioritized list, national priorities, and the availability of funding.

The overall monitoring program is under the management of the Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center (ERDC), with guidance from HQUSACE. An individual

monitoring project is a cooperative effort between the submitting District and/or Division office and CHL. Development of monitoring plans and conduct of data collection and analyses are dependent upon the combined resources of CHL and the District and/or Division.

1.2 Purpose of the study

Protecting entrances to navigation channels, harbors, or other coastal areas requires evaluating maritime structures that are often constructed with a surface layer of armor stones, such as rubble-mound breakwaters and jetties. Armor rocks are impacted by the natural deteriorating elements such as seasonal weather and repeated cycles of temperature, flowing water, wetting and drying, wave action, and freeze and thaw. The design process for the determination of armor stone sizes is complex, and various factors must be considered to fully understand how design parameters affect the stone's performance.

The outer layer of a rubble-mound coastal structure is presently designed for stability based on the dominant wave climate and tidal range anticipated over the desired life of the structure at that specific site, and on the specific gravity and quality of the available stone that will comprise the armor layer. It is inherently presumed that the same size stone will still exist at the end of the desired time period, without degradation in size due to weathering effects caused by freeze-thaw cycles, wet-dry cycles, and ice scour. At structure sites in severe climatic conditions, it is realized that armor stone degrades in size over time, losing some of its capacity to resist the wave climate for which it was designed.

The purpose of this USACE MCNP study was to evaluate and quantify major factors affecting armor stone durability. Field monitoring and laboratory testing were conducted to evaluate the performance of stone subjected to both freezing-thawing and wetting-drying and to quantify the combined effects of environmental stresses on armor stones. Additionally, long-term performance or deterioration of armor stones has been quantitatively monitored and characterized by changes in measured dimensions.

As part of the study, Armor Stone Evaluation (ARMOR) software was developed that integrates field observations with numerical tools to provide an assessment of the local freeze-thaw and wet-dry cycles on the stones. The ARMOR software has several numerical models that predict

degradation of armor stone as the rocks are impacted by natural elements. The software includes a statistical technique (homogeneity index) to characterize rock heterogeneity. Two new numerical approaches have been developed to calculate freeze-thaw cycles using long-term site weather data. The software also provides a model to estimate armor weight, minimum crest width, armor thickness, and number of armor units per unit of area. The calculation uses varying values for the seaward slope and wave height by application of the Hudson (1958) formula for rubble-mound structure stability. The degradation model relates the laboratory test results to the modification of the mass distribution and reduction at the project site.

ARMOR has been developed to ascertain the amount of degradation the stones will experience over time for given climatic conditions and stone type. Thus, ARMOR can be used as an optimizing tool to determine how oversized an armor stone should initially be to still provide the desired level of protection after the design life of the structure has passed. Alternatively, stone of different characteristics may be available but at vastly different unit prices with the better quality stone costing much more than a lesser quality stone. In such a case, ARMOR can be used to optimize the life-cycle cost of the structure by determining how much larger a less expensive but lesser-quality stone would need to be for the design life of the structure, compared to a smaller but better-quality stone at a much higher unit price.

1.3 Overview of Armor Stone Evaluation (ARMOR) numerical model

The Armor Stone Evaluation (ARMOR) computer program has varying levels of computational capabilities to forecast environmental impacts on deterioration of armor stones. The overall purpose of ARMOR is to provide an effective computational tool for the accurate and cost-effective design of armor stones for protection of coastal navigation channels, harbors, and beach areas.

The software is user friendly and efficient. Visual Basic Programming is used for the main frame of the software, while the scientific computations are performed using Fortran Programming. The software provides some of the general input data that may be used if site-specific field and laboratory data are not available.

One of the main tasks of the ARMOR software development was to verify the accuracy of developed models. For this purpose, published papers and data that used the same armor stone evaluation modeling approach were collected. The original 1991 model (Latham 1991) used in the ARMOR software has been considered in several projects by others (i.e., Cartagena, Colombia [Assen 2000]; Brindisi, Italy [Tomassicchio et al. 2003]; western Canada [Lienhart et al. 2002; Lienhart 2003]; Iceland [Tørum 2003]; and the Middle East, Bahrain [Caricato et al. 2010]).

The main purpose of those technical publications was to help specify armor stone quality requirements to improve understanding of maintenance needs in those respective coastal areas. For the ARMOR models, two prediction techniques were used: (1) the original 1991 method that was based on a wet laboratory mill abrasion test data, and (2) a later method that uses a standard table of field and geologic information, Armor Quality Designation (AQD). The in-service degradation models used in the ARMOR software calculates general wear of armor stone. As a verification of the model's accuracy, input data from Caricato et al. (2010) was placed into ARMOR, and the same output results were obtained.

Wet and dry cycle calculation methods were developed using the Arnold et al. (1996) technique. This technique uses climate and radiation data from the site. The freeze-thaw model was evaluated using freeze-thaw cycles reported in Marcus et al. (2005), an ERDC technical report pertaining to Chicago Airport and Cleveland Hopkins Airport. The next step was to use 30 years of climate data from Cleveland Harbor, Burns Harbor, and Keweenaw Waterways obtained from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) (http://www.ncdc.noaa.gov/cdo-web) to calculate freeze-thaw cycles for these areas.

2 Theory

2.1 Degradation model using mill abrasion data

Latham (1991) provided a simple approach to estimate reduction in armor rock weights resulting from several environmental and other impacts.

Factors affecting the degradation rate for armor stones include (a) the intrinsic material properties of the rock source, (b) the production-influenced geometric properties of the armor stone, (c) the environmental boundary conditions at the coastal site, and (d) the armor layer design concepts that were used (Latham 1991). Table 1 summarizes these parameters.

Table 1. Degradation rate factors for armor stone post-construction (after Latham 1991).

Type of factor	Controlling factor			Parameter
Intrinsic material properties of the rock	Mineralogy	Rock fabric strength	Resistance to weathering	k_S (see X_6)
	Micro-texture		Abrasion	k_S
	Weathering grade		Type-II impact breakage	k_S (see X_4)
	Block integrity	Block strength due to existence of macro-flaws	Type-I impact breakage	(see X_4)
Production influenced geometric properties	Block size (W_{50})			X_1
	Block grading (W_{85}/W_{15})			X_2
	Initial shape (P_R)			X_3
Environmental boundary conditions	Incident wave energy (e.g., $H^2{}_S T^2{}_m$ or H_s)			X_4
	Zone of structure			X_5
	Meteorological effects			X_6
	Water-borne attrition agents			X_7
Factors influenced by design of armor layer	Concentration of wave attack (slope angle plus tidal range)			X_8
	Armor stone mobility in design concept (e.g. $H_s \Delta D_{n50}$)			X_9

W_{50} is the median weight of blocks. W_{85} and W_{15} are the 85% and 15% lighter by weight values. PR is the Fourier Asperity Roughness parameter. H_s and T_m are the significant (i.e., average of the highest one-third waves) wave height and mean wave period, respectively. Δ is the buoyant density of rock relative to sea water, and D_{n50} is the nominal size of W_{50} block.

To apply and run this method for a given armor stone, a sample of the material is tested in an abrasion mill that simulates the wear process. The results of this test are used to provide a graph of sample weight loss versus time. Laboratory time is then converted into years of service on site using an equivalent wear-time factor that was derived from a product of nine weighted parameters. The effects of fracturing and spalling, as well as abrasion, are included.

2.1.1 Estimate of rating factors

Table 2 was adapted from Latham (1991) and provides estimates for the parameters described in Table 1. These numbers can be used as initial input parameters but should be modified according to the latest studies and publications.

Table 2. Rating range values for input to degradation model (after Latham 1991).

Parameter	Rating estimates
(k_s)	Rock fabric strength Use Abrasion mill test to plot W/W_0 versus revolutions, or select from plot of similar material tested in mill
X_1	Size effect given by 0.5 $(W_{50})^{1/3}$ for W_{50} in tones W_{50} 15 8 1 0.1 0.01 Rating (X_1) 1.23 1.0 0.5 0.23 0.11
X_2	Grading $(W_{85}/W_{15})^{1/3}$ 1.1-1.4 1.4-2.5 2.5-4.0 Rating(X_2) 1.2 1.0 0.5
X_3	Initial shape P_R >0.013 0.013-0.01 <0.010 (Asperity (irregular (equant) (semi-rounded, Roughness) tabular, rounded) Rating(X_3) 1.0 1.5 2.0
X_4	Incident wave energy Wave height H_s(m) >8 4-8 <4 Integrity of blocks good poor good poor good poor Rating(X_4) 1 0.3 2 1 3 2
X_5	Zone of structure supra-tidal inter-tidal submerged hot temperate Rating(X_5) 2.5 8 1 10

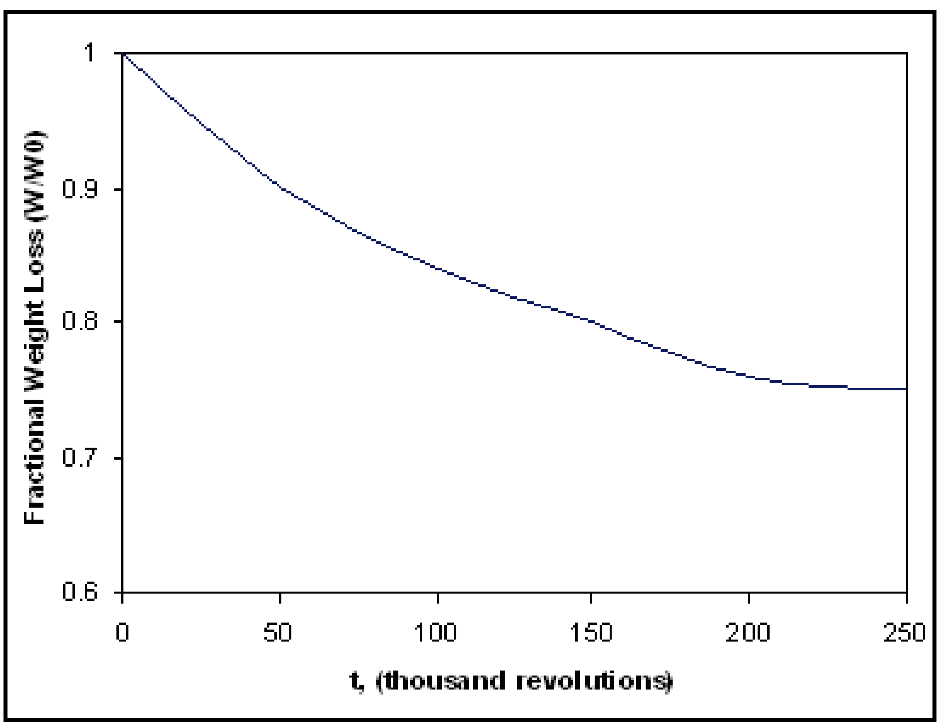
Parameter	Rating estimates
X_6	Meteorological climate-effects of specific rock types and water absorption (W_{ab}%) Hot+dry Hot+humid Freezing winters Temperate Wab>2 Wab<2 basic acidic Wab>2 Wab<2 all Rating(X_6) 0.2 0.5 0.2 0.8 0.5 1.0 1.0
X_7	Water-borne attrition agents shingle gravel sand silt none Rating(X_7) 0.2 0.5 1.0 1.2 1.5
X_8	Concentration of wave attack Tidal range(m) <2 2-6 >6 Seaward slope (cotα) <2.5 >3 <2.5 >3 <2.5 >3 Rating(X_8) 1 1.5 1.2 1.8 1.5 2.0
X_9	Mobility of armor in design concept $Hs/\Delta D_{n50}$ 1-3 4-6 6-20 (20-500) Rating(X_9) 2 1 0.5 0.2

Adapted from Latham, 1991.

2.1.2 Examples of degradation model application

Rock samples are used in the abrasion mill to create a plot of fractional weight loss versus revolutions (Figure 1). The equivalent wear time factor, X, (Equation 1) is calculated as a product of all ratings described in Table 1.

Figure 1. Typical abrasion mill test results for a specific type of armor stone (after Latham 1991).



$$X = \prod_{1}^{9} X_i \tag{1}$$

The value X is then used to convert the number of years in service to thousands of revolutions in the mill. Using Figure 1 and the number of revolutions, W/W_0 will be estimated, and the reduction in weight will be calculated.

As an example, Latham (1991) published data for two site situations given in Table 3: (a) Site 1: a 3-ton basalt in a tropical climate with medium grading and dynamic design, and (b) Site 2: a 4.5-ton basalt in temperate climate with narrow grading and static design.

Table 3. Situation summary for two basalt sites (after Latham 1991).

Parameter		Ratings	
		Site 1	Site 2
X_1	size	0.72	0.84
X_2	grading	1.0	1.2
X_3	shape	1.5	1.5
X_4	wave energy	2.0	2.0
X_5	zone	1.0	1.0
X_6	climate	0.2	1.0
X_7	attrition	1.0	1.0
X_8	concentration of attack	1.5	1.0
X_9	block mobility	1.0	2.0
X	equivalent wear time factor	0.6	6.0

2.2 Degradation model using AQD method

2.2.1 Overview of AQD degradation method

The Armor Quality Designation (AQD) method is based on published papers by Latham (1991), Leinhart (1998, 2003), and Latham et al. (2006). The model calculates a parameter that represents the site aggressiveness (Equivalent Wear Time Factor, X), and a parameter that represents the intrinsic durability of the rock (intrinsic resistance to mass loss, k_s), and uses them to estimate mass loss over time with Equation 2.

$$\frac{\boldsymbol{M}}{\boldsymbol{M}_0} = 0.05\,\boldsymbol{exp}\left[-30\left(\frac{\boldsymbol{k_S T}}{\boldsymbol{X}}\right)\right] + 0.95\,\boldsymbol{exp}\left[\frac{-\boldsymbol{k_S T}}{\boldsymbol{X}}\right] \tag{2}$$

where:

M = nominal mass of armor stone at time T,
M_o = initial mass of armor stone,
k_S = intrinsic resistance to mass loss,
X = equivalent wear time factor, and
T = time since installation (years).

The intrinsic resistance to mass loss, k_s, is an intrinsic property of the rock material and describes the resistance to weathering. The value of k_s may be obtained from Equation 3. For the AQD method, a number of indicators of rock quality are combined with a weighted average system, or value, as AQD used in Equation 3. The AQD method takes into account a much greater number of relevant factors when assessing k_s; thus, the AQD method may be preferred over the degradation model using mill abrasion data described in Section 2.1 of this document.

$$k_S = 0.032(AQD)^{-2.0} \quad (3)$$

ADQ may be calculated using data and selected quality rating shown in Table 4. The user selects the quality rating based on the armor stone type.

The Equivalent Wear Time Factor, X, reflects the rock size, grading, and shape, and the conditions to which the rock is subjected (wave conditions, climate, waterborne attrition, etc.). Nine parameters designated X_1 to X_9 represent the various factors affecting weathering rates on site (e.g., wave impact, X_4; climatic weathering, X_6; and waterborne attrition agents, X_7). When this option is running, a table of parameters (such as Table 4) will appear on the main windows of the software for the user to select appropriate values. These values are based on the field properties such as significant wave height, climate statistics, and type of waterborne attrition agent. Finally, the overall Equivalent Wear Time Factor, X, is calculated as the product of each of these parameters given in Equation 2.

2.2.2 Determination of the intrinsic resistance to mass loss

One of the advantages of the AQD method is that properties that are not available from field evaluations and laboratory tests do not need to be included in the determination of the AQD value. The weighted average AQD value can be calculated from parameters that are available. Table 4 may be

used to estimate AQD value. The user needs only to select a Quality Rating (1, 2, 3, or 4) and place it on the table column assigned as “Average.”

Previously, in Section 2.1 of this document (Degradation model using mill abrasion data), the value of k_s is calculated from an abrasion mill laboratory test. For the AQD method, the value of k_s that is needed to calculate reduction of armor stone mass can be obtained from Equation 3 by using parameters from Table 4.

Table 4. Example of quality rating assessment worksheet (after Lienhart 1998).

	a	b				c	d	e
	Criterion	Quality rating				Rating value	Weighting	Weighted rating
		Excellent	Good	Marginal	Poor			
		4	3	2	1	Average	%	[(c) x (d)]/ [mean of (d)]
Field-based Indicators	Lithological classification						58	
	Regional *in situ* stress						73	
	Weathering grade						73	
	Discontinuity analysis						95	
	Groundwater condition						73	
	Production method						95	
	Rock block quality						80	
	Set-aside						73	
	Petrographic evaluation						95	
1	Block integrity test						90	
	Block integrity visual							
2	Mass density						80	
	Rock adsorption							
	Microporosity / total porosity							
	Methylene blue absorption							
3	Compressive strength						88	
	Sediment impact index							
	Sonic velocity							

	a	b				c	d	e
	Criterion	Quality rating				Rating value	Weighting	Weighted rating
		Excellent	Good	Marginal	Poor			
		4	3	2	1	Average	%	[(c) x (d)]/ [mean of (d)]
4	Point load strength						88	
	Fracture toughness							
	Los Angeles							
5	Micro-Deval						88	
6	Freeze-thaw loss						80	
	MgSO4 soundness							
	Wet-dry loss							
						Sum	1229	
						n	15	
						Mean	81.9	

This example includes 15 factors (nine field factors, six laboratory factors); hence overall rating or Armor Quality Designation (AQD) is the mean of column (e) based on all 15 factors. If no data are available for one or more factors, AQD should be based on the number of induced factors. A complete and balanced set of data is ideal.

In addition to engineering geology indicators, each boxed grouping of tests 1 to 6 generates one average rating value in column (c) from one or more suggested tests. They refer to (1) resistance to major breakage, (2) mineral fabric physical quality, (3) resistance to minor breakage (compressive), (4) resistance to minor breakage (tensile, dynamic), (5) resistance to water (shear and attrition), and (6) resistance to in-service weathering.

Test results and field assessment can be used to generate a continuously varying rating from 0.5 to 4.5 rather than integer values (numbers). Similarly, AQD results can vary from 0.5 to 4.5.

2.3 Meteorological Climate Weathering Intensity (MCWI)

The intensity of the weathering regime at the project site has a large effect on how well the selected stone will endure. Lienhart (2003) provides Equation 4 showing the factors that must be considered when analyzing the site climatology. This number is called the Meteorological Climate Weathering Intensity (MCWI) index. The input climate data required to calculate MCWI are available from NOAA NCDC web site, for each state and observation location.

$$MCWI = (a/b)\ x\ (d/365)\ x\ (e/c)\ x\ ((g/f)\ x\ h) \tag{4}$$

where:

a = mean (max) - mean (min) temperature range over several years,
b = mean annual temperature,
c = mean number of days max temp > freezing,
d = mean number of days min temp <= freezing,
e = extreme max and min temperature range over several years,
f = mean number of days with precipitation > 0.01 in. (0.25 mm),
g = annual precipitation in cm, and
h = total normal degree-days, base 65°F (18°C).

The parameter X_6 (Table 1) represents the aggressiveness of the local meteorological or climate conditions. The X_6 value is a function of the MCWI index (Lienhart 2003).

2.4 Characterization of rock heterogeneity

Liu et al. (2004) describes a statistical approach (homogeneity index) to characterize the heterogeneity in rocks. According to Liu et al. (2004), the Weibull distribution (Weibull 1951, Hudson and Fairhurst 1969) describes very well the experimental data for the distribution of microstructures within the rock.

The strength of brittle materials such as rock exhibits a degree of scatter that may be characterized using a cumulative distribution function originally proposed by Weibull (1951). The Weibull distribution for brittle materials such as rock may be simplified as Equation 5.

$$Q(\sigma) = \int_0^{\sigma} P(x)dx = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right] \tag{5}$$

where:

Q = the cumulative distribution,
σ = the elemental parameter (MPa),
P = the Weibull probability density function,
m = the shape parameter describing the scatter of σ and the heterogeneity of the rock, and
σ_0 = the mean value of the physical-mechanical parameters of the specimen (elemental parameter).

The recommended method for calculating the homogeneous index, m, (Curtis and Juszczyk 1998, Davies 2001) is to rank strength (σ) data from smallest to largest and to assign respective Q(σ) values according to Equation 6:

$$Q(\sigma) = \frac{i}{N+1} \tag{6}$$

where i is the rank and N is the total number of specimens. According to Equation 6, the Weibull distribution can be liberalized into the following Equation 7:

$$y = \ln\left[\ln\left(\frac{1}{1-Q(\sigma)}\right)\right] = m\ln\sigma - m\ln\sigma_0 = Ax + B \tag{7}$$

where y = ln [ln {1/[1 - Q(σ)]}], A = m, x = ln σ, and B = -m ln σ_0. With reference to this equation, a plot of x = ln σ versus y = ln [ln {1/[1 - Q(σ)]}] gives the line-relationship, and the slope of the line is the homogeneous index, m. The best estimate of the homogeneous index, m, may be obtained using the linear least squares (LLS) techniques of Equation 8 (Davies 2001). The parameter, B, may be obtained from Equation 9,

$$m = A = \frac{n\sum xy - \sum x \sum y}{n\sum x^2 - (\sum x)^2} \tag{8}$$

$$B = \frac{\sum x^2 \sum y - \sum x \sum xy}{n\sum x^2 - (\sum x)^2} \tag{9}$$

where $\sum$, x, and y in the Equations 8 and 9 are abbreviations for $\sum_{i=1}^{n}$, x_i and y_i, respectively.

One of the attractive aspects of the Weibull distribution is the presence of the shape parameter, m, which allows this function to take a wide variety of shapes. For m = 1, the distribution is exponential. At about m = 1.5, the distribution is nearly log-normal. At about m = 4, it closely approximates a normal distribution. Since the shape parameter, m, is a measure of the element parameter variability, it can be considered as a homogeneity index. The larger the index m, the more homogeneous is the rock. When m tends to infinity, the variance tends to zero, and an ideal homogeneous

rock is obtained. Kim and Yao (1995) described micromechanical modeling analyses of brittle rock and found that specimens with a lower shape parameter, m (more heterogeneous specimens), showed widely dispersed microstructure throughout the test specimen. In specimens with higher shape parameter, m (more homogenous cases), the micro-cracks tended to occur in narrowly confined areas.

Two statistical techniques are used in the software to calculate the homogenous index, m: (1) least-square estimation of logarithmic transformed data, and (2) maximum-likelihood (ML) estimator. ML is a procedure of finding the value of one or more parameters for a given statistic that makes the known likelihood distribution a maximum.

An important feature of the above strength analysis is that a large number of test specimens need to be broken before the Weibull parameters can be estimated with acceptable accuracy (Fok and Smart 1995). For example, at least 30 specimens need to be tested before m is obtained within 20% accuracy (Green 1998). It is not unusual to require 40-50 specimens before proceeding with a strength-testing program. It is also important to consider that specimen size can be critical for attaining valid comparisons of the Weibull parameters among several types of materials, including rocks. The specimen with the larger volume is predicted to possess the lower strength simply because there is an increased probability of "finding" a larger flaw in a larger body. For consistency reasons in analyzing the results, special attention should be taken in the selection of the specimen dimensions as well as in its preparation.

2.5 Estimation of freeze-thaw intensity by Lienhart method

The intensity of freezing and thawing depends on the freezing temperature, the duration of the freezing cycle, the available moisture, the slope direction (geographic area properties), the degree of saturation, and permeability (rock properties). Lienhart (1998) describes the following technique (formulation) of Equation 10 to measure the intensity of freezing and thawing:

$$MNFC = \sum_{i=1}^{12} \left(MNMaxT - MNMinT \right)_i \tag{10}$$

where:

MNFC = mean number of freezing cycle (days/year),
MNMaxT= mean number of days of maximum temperature of 32° F and below for each month, and
MNMinT= mean number of days of minimum temperature of 32° F and below for each month.

Since the amount of moisture affects the freeze-thaw durability, the mean number of days of precipitation (MNDP) of 0.01 in. or more for those months in which freezing cycle days occur was also calculated. The percentage of days of precipitation (PP) of 0.01 in. or more during the freezing cycle month is given as Equation 11.

$$PP = \frac{MNDP}{(MNMaxT - MNMinT)} \tag{11}$$

The moist freeze-thaw index (MFTI) may then be calculated from Equation 12 as:

$$MFTI = \sum_{i=1}^{12} ((MNMaxT - MNMinT) \times PP)_i \tag{12}$$

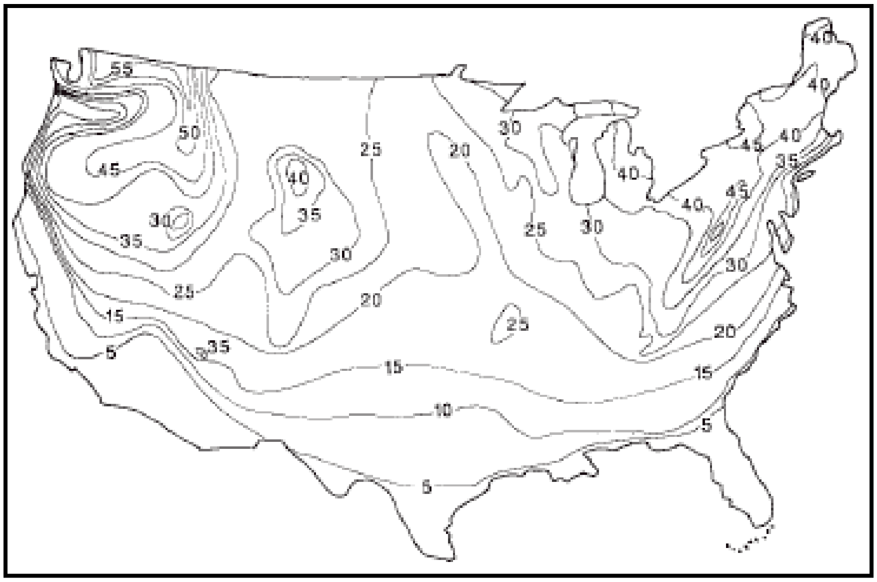
Lienhart (1998) used data from 254 weather stations from the National Oceanic and Atmospheric Administration (NOAA) and plotted the calculated moist freeze-thaw index for the contiguous United States (Figure 2).

The intensity of a freezing and thawing environment depends on:

- freezing temperature,
- duration of the freezing cycle,
- available moisture,
- slope direction,
- degree of saturation, and
- permeability.

The first four of the above factors depend on geographic area, and the last two factors are rock properties; hence, the freeze-thaw intensity must be mainly dependent on geographic area (Lienhart 1998).

Figure 2. Isoline map of the moist freeze-thaw index for the United States (after Lienhart 1998).



2.6 Estimation of freeze-thaw cycles by Arnold method

Arnold et al. (1996) proposed a new technique to calculate freeze-thaw cycles. This technique differed from the Lienhart (1998) technique in three ways: (1) a 5-day mean temperature and rainfall were used to define freezing and thawing cycles, (2) moisture was computed for the upper 1 in. of surface material and not from precipitation alone, and (3) more than 5,000 stations were utilized to define the index.

For this present MCNP study, the technique of Arnold et al. (1996) was modified as follows. The program calculates mean daily temperature and compares it with 32°F (when the mean daily temperature is below 32°, it is identified as freezing; when above 32°, thawing). For each day of each month that the index of freezing or thawing occurs in that day, one number will be added to the total number of indexes (cycles). Divide the final number for each month by 2 and multiply by percentage of precipitation (greater than 0.01 in.). The index for the year is the sum of the monthly indexes.

2.7 Estimation of wet-dry index

Arnold et al. (1996) provided a method to calculate a wet-dry index. The wet-dry index delineates the average number of wet-dry cycles per year for the surface material. For this technique, potential evapo-transpiration (ET) is calculated using the method of Priestley and Taylor (1972) and

solar radiation and air temperature. A wet-dry cycle is counted when the soil water reaches zero after being at a maximum water storage capacity (7.6 mm) and when it reaches the maximum after being at zero. A flow chart for the wet-dry index algorithm is given in Figure 3.

2.8 Damage estimation of armor stone

The damage estimation used in the ARMOR software is based on extensive research work conducted at ERDC (Melby and Kobayashi 1998a, 1998b; Melby 2005). The method calculates damage progression on a rubble-mound breakwater, revetment, or jetty trunk armor layer by water wave actions. The method applies to uniform-sized armor stone ($0.75W_{50} \leq W_{50} \leq 1.25W_{50}$, W_{50} = median weight of armor stone) as well as riprap ($0.125W_{50} \leq W_{50} \leq 4W_{50}$) exposed to depth-limited wave conditions.

Rubble-mound breakwater, revetment, and jetty projects require accurate damage predictions as part of life-cycle analyses. The damage option provided in the ARMOR software determines damage progression on stone armor layers for variable wave conditions over the life of a structure. Damage occurs as a result of a sequence of storms of varying severity and with varying water levels. This section provides equations that allow the prediction of rubble-mound deterioration with time.

Damage is defined here in terms of the average normalized cross-section eroded area of armor on the slope. Damage is defined up to the point that the under layer is exposed through a hole the size of a nominal armor stone diameter, $D_{n50} = (M_{50}/\rho_a)^{1/3}$, where M_{50} is the median mass of armor stone and ρ_a is the armor stone density. The condition in which the under layer is exposed defines failure of the armor layer because rapid destruction of the structure often occurs after this point. The damaged profile is described in terms of three engineering parameters: (1) maximum eroded depth ($E = d_e/D_{n50}$), (2) minimum remaining cover depth($C = dc/D_{n50}$), and (3) maximum cross-shore length of the eroded region ($L = l_e/D_{n50}$). Broderick and Ahrens (1982) defined damage to an armor layer by the normalized eroded cross-section area as $S = Ae/(D_{n50})^2$, where A_e is the measured eroded cross-section area. These damage descriptors are shown in Figure 4.

Figure 3. Flow chart of the wet-dry index algorithm (after Arnold et al. 1996).

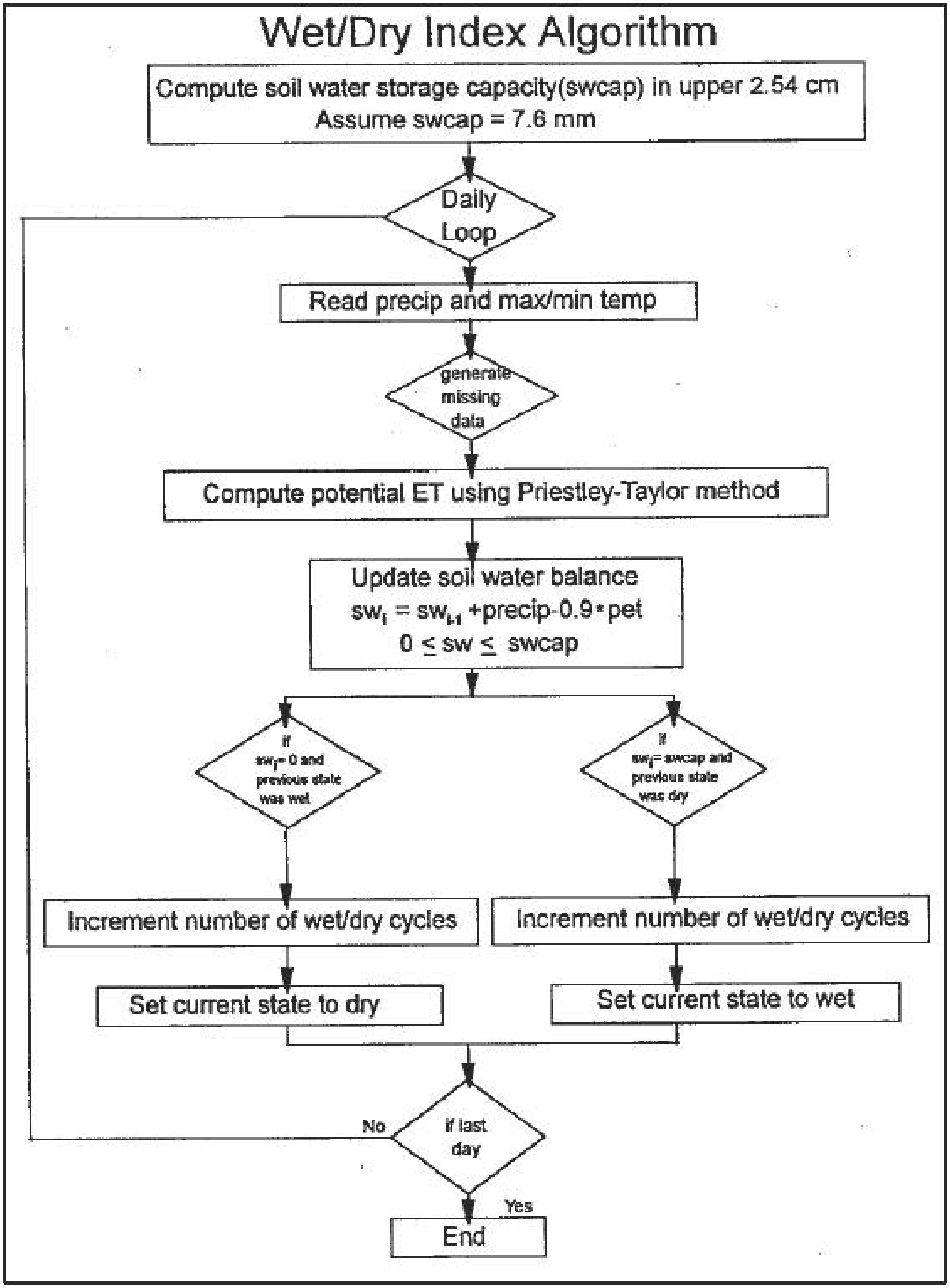
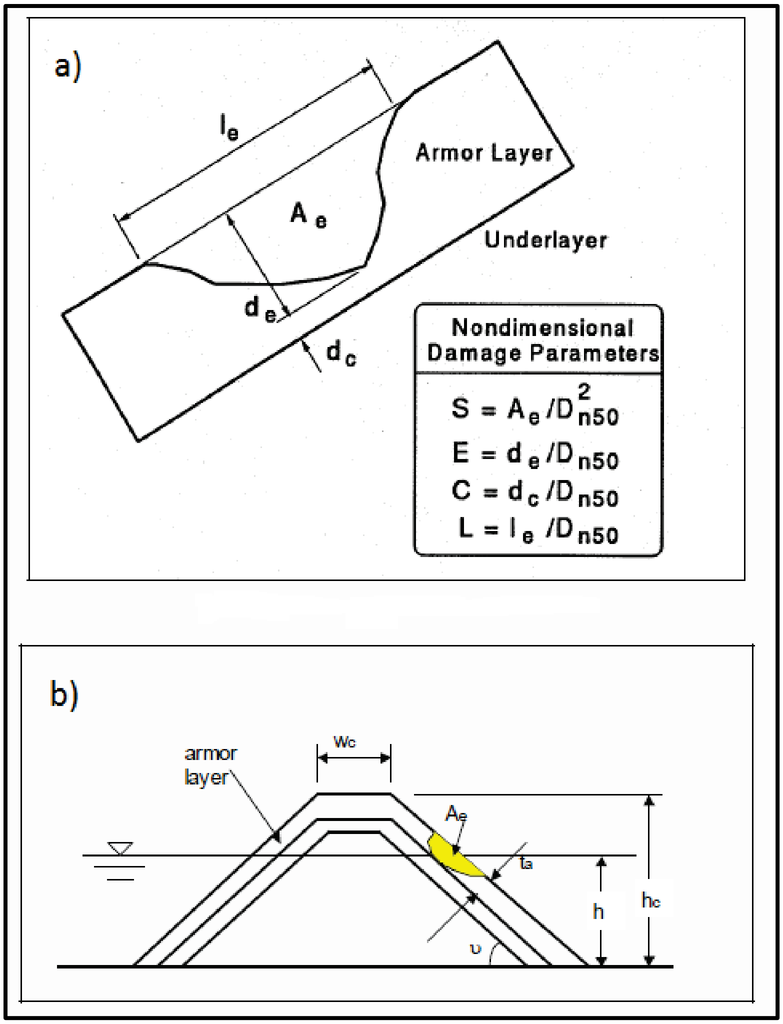


Figure 4. Illustration of (a) damaged section parameters, and (b) rubble-mound structure cross section (after Melby 2005).



Melby and Kobayashi (1998a, 1998b) conducted a series of experiments measuring the erosion of a stone armor layer for varying wave- and water-level conditions. The structure profile was measured repeatedly throughout the test at up to 32 sections along the structure. The 32 profiles were used to obtain a mean damage profile, as well as to determine the variability of damage along the structure.

The empirical equation proposed by Melby and Kobayashi (1998a, 1998b) for predicting the temporal progression of the mean eroded area as a function of time domain wave statistics is Equation 13:

$$\overline{S}(t) = \overline{S}(t_n) + 0.025 \frac{(N_s)_n^5}{(T_m)_n^{0.25}} (t^{0.25} - t_n^{0.25}) \quad for \quad t_n \le t \le t_{n+1} \qquad (13)$$

where $\bar{S}$(t) and $\bar{S}$(t_n) are predicted and known mean eroded areas at times t and t_n, respectively, with $t > t_n$. $N_s = H_s/(\Delta D_{n50})$ is the stability number based on the average of the highest one-third wave heights from a zero-upcrossing analysis, $\Delta = S_r - 1$ where S_r is the armor stone specific gravity, and T_m is the mean period. The wave parameters are defined at $5H_s$ seaward of the structure toe, which is the travel distance of large breaking waves. Equation 13 provides a means to compute damage over a sequence of N events, each of relatively constant wave conditions, where each event is defined over a time period from t_n to t_{n+1}.

The mean parameters $\bar{S}$, $\bar{E}$, $\bar{C}$, and $\bar{L}$ and the standard deviations σ_S, σ_E, σ_C, and σ_L, were used to describe the tendencies, variability, ranges of damage, and the damaged profile, respectively. All measured values of S, E, and C, from all measured series, were in the following ranges of Equations 14 through 16:

$$\text{Damage: } -2.7 < (S - \bar{S})/\sigma_S < 3 \qquad (14)$$

$$\text{Eroded Depth: } -2.7 < (E - \bar{E})/\sigma_E < 2.7\text{, and} \qquad (15)$$

$$\text{Cover Depth: } -2.7 < (C - \bar{C})/\sigma_C < 2.8 \qquad (16)$$

These ranges allow the lower and upper limits of the damaged profile descriptors to be estimated. To reduce the number of parameters for design, Melby and Kobayashi (1998a, 1998b) expressed the key profile parameters as a function of the mean damage $\bar{S}$ as Equations 17 through 20:

$$\sigma_S = 0.5\,\bar{S}^{\,0.65}, \qquad (17)$$

$$\bar{E} = 0.46\,\bar{S}^{\,0.5}, \qquad (18)$$

$$\bar{C} = C_o - 0.1\,\bar{S}\text{ , and} \qquad (19)$$

$$\bar{L} = 4.4\,\bar{S}^{\,0.5} \qquad (20)$$

where C_o is the initial cover depth (dimensionless). The initial layer thickness is given as $t_r = 2D_{n50}$.

2.9 Hudson design model

The design process for the determination of stable and economical armor stone sizes is complex. Various factors must be considered to fully understand how the design parameters have an indirect effect on stone performance. Two of the more useful of the design equations are introduced here to demonstrate the influence of these factors.

A design evaluation formula for an armor stone should be a method of determining mass (weight) of individual armor units for given mass densities required for stability as a function of all the environmental parameters involved. Hudson (1959) developed the well-known design equation for determination of acceptable armor stone size to resist damage from a given wave system based on hydraulic modeling studies (Equation 21):

$$W = (H^3 w_r) / (K_d (S_r - 1)^3 \cot\theta) \tag{21}$$

where W is the weight of the armor unit, H is the average wave height of the highest 10% of all waves, w_r is the unit mass of the stone, K_d is a damage coefficient (stability coefficient), S_r is the specific gravity of the stone, and θ is the angle of the slope of the armor stone.

Equation 21 was developed for conditions when crest of the structure is high enough to prevent major overtopping. Cover layer slopes steeper than 1-to-1.5 are not recommended by the USACE (2011) (*Coastal Engineering Manual).*

Hudson (1959) conducted an extensive series of experiments to obtain basic information on the stability, K_d, of rubble-mound breakwaters. K_d varies primarily with the shape of the armor units, roughness of the armor unit surface, sharpness of edges, and degree of interlocking obtained in placement. Table 5 provides recommended values for various type rocks and placements, extracted from the USACE (2011) *Coastal Engineering Manual*.

The Armor Stone Evaluation (ARMOR) software developed for this project may be used to estimate the armor weight, minimum crest width, armor thickness, and number of armor units per unit area of a breakwater using varying values for the seaward slope and wave height, and K_d from Table 5.

Table 5. Suggested K_D values for the Hudson equation (after USACE 2011).

No-Damage Criteria and Minor Overtopping							
			Structured Trunk		Structured Head		
			K_D		K_D		Slope
Quarry Stone	Armor Unit (n)	Placement	Breaking Wave	Non-breaking Wave	Breaking Wave	Non-breaking Wave	Cotϴ
Smooth rounded	2	Random	1.2	2.4	1.1	1.9	1.5 to 3.0
Smooth rounded	>3	Random	1.6	3.2	1.4	2.3	
Rough angular	1	Random		2.9		2.3	
Rough angular	2	Random	2.2	4.5	2.1	4.2	5
Rough angular	>3	Special	5.8	7.0	5.3	6.4	5
Parallelepiped	2	Special	7.0-20.0	8.5-24.0	--	--	
Tetrapod and quadripod	2	Random	7.0	8.0	5.0	6.0	1.5
					4.5	5.5	2.0
					3.5	4.0	3.0
Tribar	2	Random	9.0	10.0	8.3	9.0	1.5
					7.8	8.5	2.0
					6.0	6.5	3.0
Dolos	2	Random	15.8	31.8	8.0	16.0	2.0
					7.0	14.0	3.0
Modified cube	2	Random	6.5	7.5	-----	5.0	5
Hexapod	2	Random	8.0	9.5	5.0	7.0	5
Toskane	2	Random	11.0	22.0	--	--	5
Tribar	2	Uniform	12.0	15.0	7.5	9.5	5
Quarry stone (K_{RR})							
Graded angular	-	Random	2.2	2.5	--	--	

The following example illustrates the flexibility of the design depending on the availability of various qualities of stone. Assuming the following conditions:

W = W_{50} or the median size armor required, kg,
H = design wave height = 20 ft,
w_r = 168.49 lb/ft^3 (unit weight),
S_r = 2.70 specific gravity (dimensionless),
ϴ = 21.8° slope, or 2.5 horizontal on 1 vertical, and

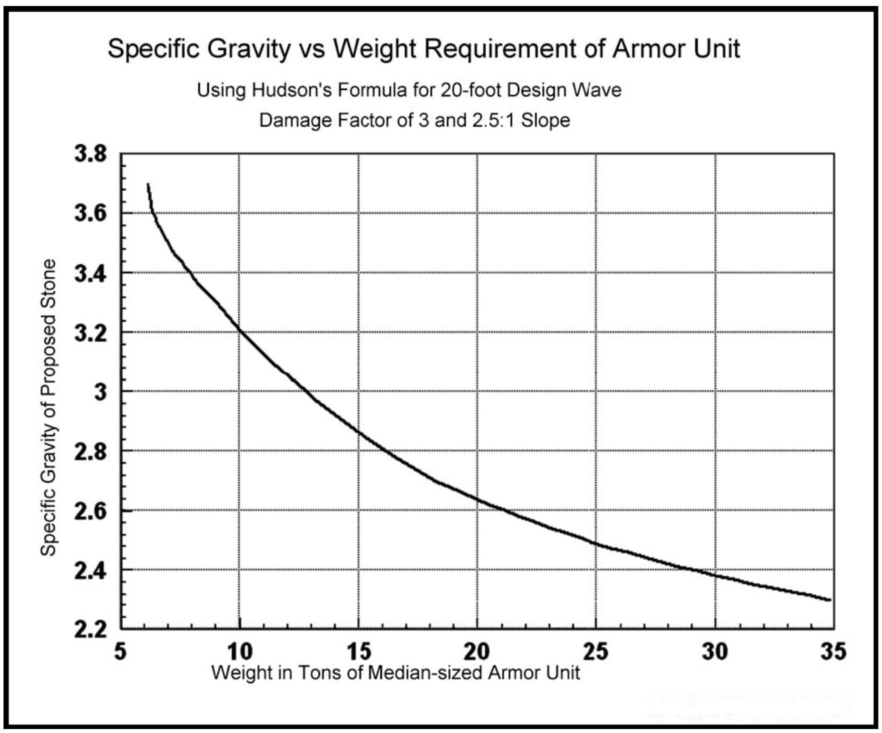
K_d = a damage coefficient of 3.0 (assuming trunk, breaking waves, rough stone, and two layers of armor).

Inputting parameters into Equation 21:

$$W_{50} = ((20)^3 \times 168.49)/(3.0 \times (2.7 - 1)^3 \times 2.5) = 36{,}580 \text{ lbs} = 18.3 \text{ tons}$$

For another rock type with a unit mass of 205.92 lb/ft^3 and specify gravity of 3.3, the armor stone weight would be 18,051 lbs or 9.03 tons. Figure 5 shows how stone weight changes for various types of rocks with different specific gravity.

Figure 5. Specific gravity versus weight requirement of armor unit.



The Hudson formulation has been used for armor stone design more than other formulations because of its simplicity in application. Other formulations such as Van der Meer (1987) developed for plunging (breaking) waves and for surging (non-breaking) waves in deep water conditions may also be used for armor stone design. Because a sensitivity analysis must be performed for each of the parameters in Van der Meer's equations, these equations are more difficult to use than the Hudson equation.

The Van der Meer (1987) equations are Equations 22 and 23:

$$\frac{H_S}{\Delta D_{n50}} = 6.2\, P^{0.18} (S / \sqrt{N})^{0.2} \xi_m^{-0.5} \text{, for plunging waves, and} \quad (22)$$

$$\frac{H_S}{\Delta D_{n50}} = 1.0\, P^{-0.13} (S / \sqrt{N})^{0.2} \sqrt{\cot\alpha}\, \xi_m^{P} \text{, for surging waves} \quad (23)$$

where:

H_S = significant wave height at structure toe,
Δ = density correction for armor stone in sea water,
D_{n50} = nominal diameter of stone,
6.2 and 1.0 = numerical constants (for plunging waves under shallow water conditions, the numerical constant may range from 6.2 to 7.7; for surging waves the constant may range from 1.0 to 1.4),
P = theoretical permeability coefficient of the structure,
S = damage level depending on slope angle and ranges from 2 to 17,
N = number of waves up to a maximum of 7,500,
ξ_m = parameter describing the form of the wave breaking on the structure, and
α = slope angle of the breakwater from horizontal.

Another aspect of design is that stones with different sizes can be used, with identical mass but with varying specific gravity. Numerous conflicts have arisen because of the differences between the stipulated stone specific gravity and the actual specific gravity of stone as delivered from the quarry to the field site. As already seen in the design equations, delivering a larger block of stone can compensate for this difference. Consider the following stones with a shape midway between a cube and a sphere:

- For a stone of specific gravity of 2.50 and a mass of 6.40 tons, the diameter would be 55.5 in.
- For a stone of specific gravity of 2.70 and a mass of 6.40 tons, the diameter would be 54 in.
- For a stone of specific gravity of 3.30 and a mass of 6.40 tons, the diameter would be 51 in.

This variation amounts to a diameter difference of only 11.4 cm or 4.5 in. between a stone of specific gravity 2.50 and one of 3.30. The difference in size would be difficult to detect by the average construction inspector, but illustrates that specific gravity has little effect on size requirement and is the reason that armor stone is specified by weight requirements.

3 Getting Started with ARMOR

3.1 Computer requirements

The software ARMOR was developed for personal computers (PC), either desktop or laptop client-based applications, meaning the entire program and files reside on the user's PC. The software is currently distributed by CD or DVD, and a copy can be requested from ERDC, GSL.

ARMOR software is currently distributed by CD or DVD. A copy may be obtained from Dr. Mansour Zakikhani, U.S. Army Engineer Research and Development Center, Environmental Laboratory, 3909 Halls Ferry Road, Vicksburg, MS; (Mansour.zakikhani@usace.army.mil); phone 601-634-3806.

The user should have a technical background with some knowledge or training in coastal or hydraulic engineering. ARMOR software requires a minimum of 900 megabytes (MB) of hard disk space, and two gigabytes (GB) of random access memory (RAM).

3.2 Installing software

The user simply inserts the CD or DVD of ARMOR software into the PC's DVD drive, and the software will be installed to the PC. In a case where software cannot be started automatically, the user should go to the CD or DVD directory and click on the *setup.exe*.

3.3 Launching ARMOR

After ARMOR software has been installed, an icon labeled "Armor-Stone" appears on the user's PC desktop for launching ARMOR. Double clicking this icon will launch the program, and the main screen of the user interface (UI) will come up on the PC screen.

4 Main Screen Features

The main screen of the ARMOR stone software is shown in Figure 6. There is one major feature (a white menu bar) showing options available for use. The blue menu bar underneath the white menu bar shows only the software title. The 12 options available for use on the white menu bar include the following:

Figure 6. Main window of the Armor Stone Evaluation (ARMOR) numerical simulation model.

4.1 Meteorological Climate Weathering Intensity (MCWI)

The options under *MCWI* are:

- *Input Data*,
- *Run MCWI Model,*
- *Output MCWI*, and
- *Exit*.

Input Data is used to select climate data. The data can be created (*New Data*) or be selected from an existing data set (*Existing Data*).

Run MCWI Model is used to execute the model.

Output MCWI is selected to open an output file.

Exit is used to close the software.

4.2 Model Input Data

The options under *Model input Data* are:

- *Open Existing Data,*
- *Create New Data,* and
- *Exit*.

Open Existing Data is used to select existing input data for an available list of models.

4.3 Mill Abrasion Data

The options under *Mill Abrasion Data* are:

- *Input Data,*
- *Show Plot,* and
- *Show Plot in Excel*.

Mill Abrasion Data are needed to run the Degradation Rate model. Values for three parameters are used to create the Mill Abrasion graph (plot). *Show Plot* provides a general graph of the Mill Abrasion Data. *Show Plot in Excel* provides an Excel formatted graph.

4.4 Models

The options under *Models* are:

- *Degradation Rate,*
- *Degradation AQD,*
- *Freeze-Thaw Index,*
- *Wet and Dry Cycle,*
- *Rock Heterogeneity,* and
- *Damage Calculation*.

4.5 Model Output Results

The options under *Model Output Results* are:

- *Degradation Output,*

- *Degradation AQD Output,*
- *Freeze and Thaw Output (Lienhart technique),*
- *Freeze and Thaw Output (Arnold technique),* and
- *Wet and Dry Output (Arnold technique).*

4.6 Deterioration (years of service)

The options under *Deterioration (years of service)* are:

- *Degradation Rate (Mill Abrasion Use),* and
- *Degradation AQD (AQD Worksheet).*

4.7 Hudson Design Model

The options under *Hudson Design Model* are:

- *Input Data,*
- *Run Design Model,* and
- *Model Output.*

4.8 Optimization

This option is not available with this version.

4.9 Statistical Analysis

This option is not available with this version.

4.10 Films

Open Films screen shows a list of available videos to play.

4.11 Photos

This option is not available with this version.

4.12 Help

The user can access useful information in MS-Word files about the models and data input. (For some PCs, the user may need to minimize the software to see the MS-Word file.)

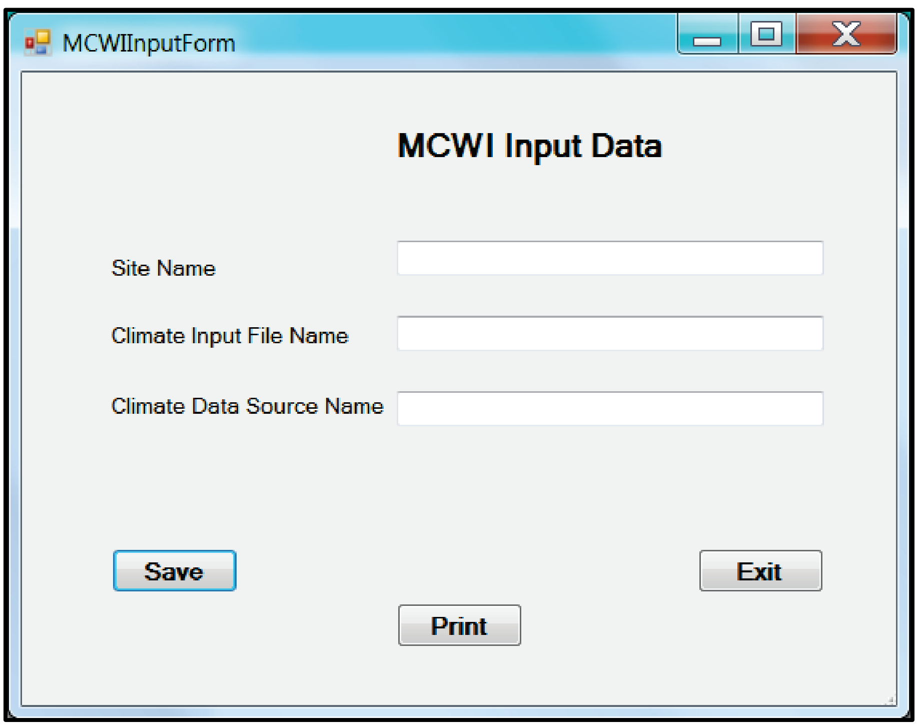
5 Model Input, Simulation, and Output

This chapter provides basic guidelines on (1) data requirements for each model, and (2) running and creating output for each model and option of the software. This chapter presents all of the input screens for each model. Inputs are self-explanatory and are relatively easy to follow with the help screens.

5.1 Meteorological Climate Weathering Intensity (MCWI)

When the user clicks *MCWI, Input Data,* and *New Data,* a screen opens as in Figure 7:

Figure 7. View of MCWI input data.



where *Site Name* is the site name*, Climate Input File Name* is the name of climate data in CSV format (including .csv), *and Climate Data Source Name* is the name of the data source. Here, the NOAA NCDC is used as the data source.

MCWI requires climate data for the site, which is available from the NOAA NCDC web site (http://www.ncdc.noaa.gov). The format of data is in the CSV file

type (file with .csv extension). A data sample is given in Figure 8. This file type is often associated with Microsoft Excel, as this is one of the standard ways to transfer data into and out of a spreadsheet. The last row of the CSV (Excel) file has to be as shown in Table 6. Examples of input data will be provided with the DVD distribution disc, and the user can utilize it to format new data downloaded from the NOAA NCDC for other sites. The size of each column of data in an Excel file must be exactly eight digits of numbers and spaces; otherwise, the software cannot read the input data. For example, if the data entry is 777, the data in the Excel file column occupies (777) with five blank spaces preceding the number.

In Table 6, *Date* includes year, month, and day of collected data; *PRCP* is precipitation in inches; and T_{max} and T_{min} are maximum and minimum temperature in Fahrenheit (°F), respectively.

Figure 8. View of MCWI output.

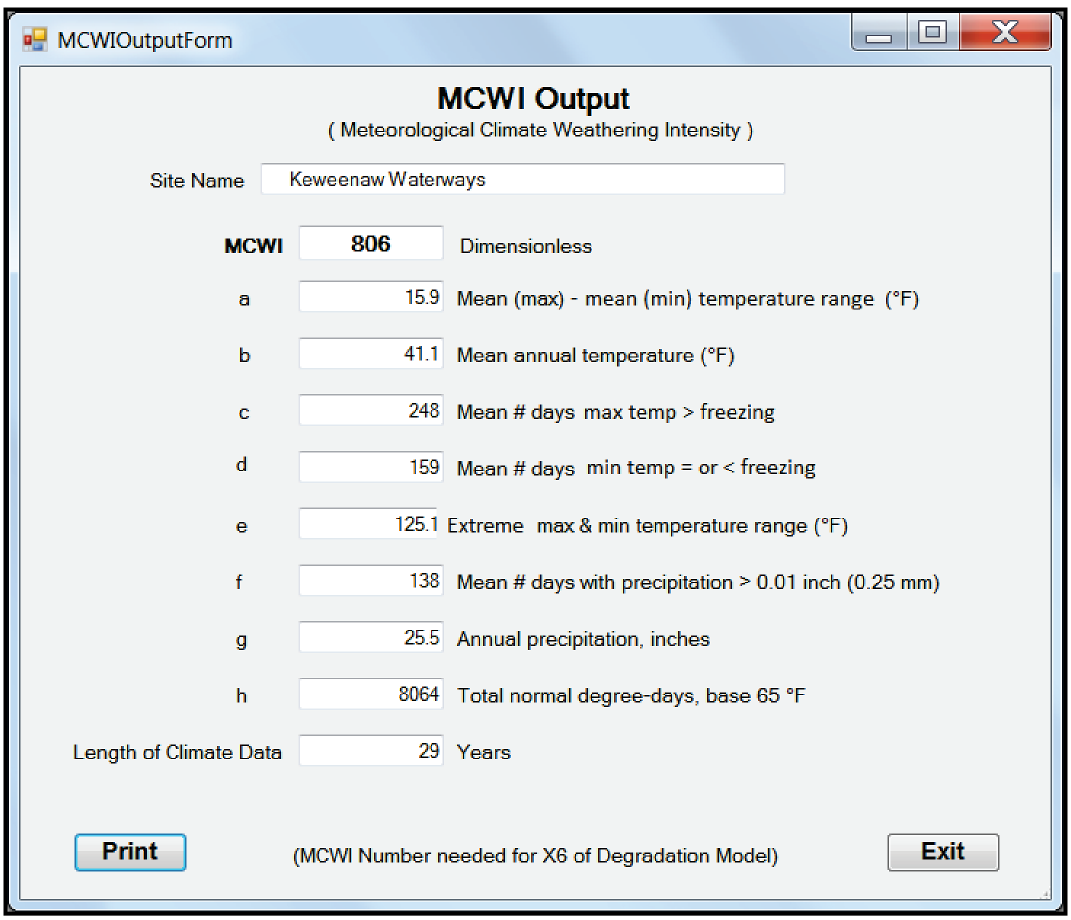


Table 6. Example of climate input data showing format of data.

Cleveland Harbor, Ohio			
Date	PRCP (in.)	T_{max}	T_{min}
19990101	0	-72	-100
19990102	89	6	-106
19990103	20	22	-100
19990104	0	-94	-150
19990105	0	-128	-183
19990106	3	-11	-128
19990107	0	-67	-117
19990108	28	-33	-111
19990109	3	-33	-94
88888888	888	888	888

After providing the site name, the climate input file name, and the climate data source name, the user must save the file and use option *Run MCWI Model* to execute the model. The output can be viewed by selecting *Output MCWI*, as shown in Figure 8 for Keweenaw Waterways. The user needs only the MCWI value for the selection of the X_6 value for the degradation model input. Other calculated values in Figure 8 are provided in case the user needs them for other applications.

5.2 Model input data

Chapter 4 of this document provided a summary of what is available in the software. Here, use of the options is presented.

The options under *Model Input Data* are:

- *Open Existing Data,*
- *Create New Data*, and
- *Exit*.

Open Existing Data is used to select existing input data files from the available list of models. Under this list, six models are available for selection (click).

- *Degradation Rate,*
- *Degradation AQD,*
- *Freeze-Thaw Index,*

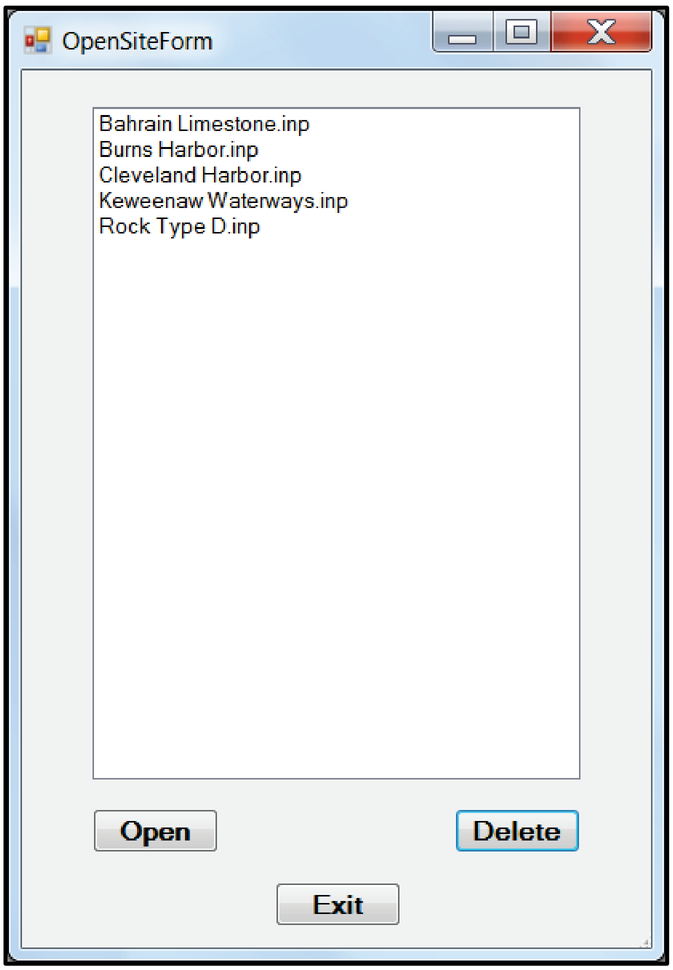
- *Wet and Dry Cycle*,
- *Rock Heterogeneity*, and
- *Damage Calculations*.

5.3 Model selection and run

5.3.1 Degradation rate

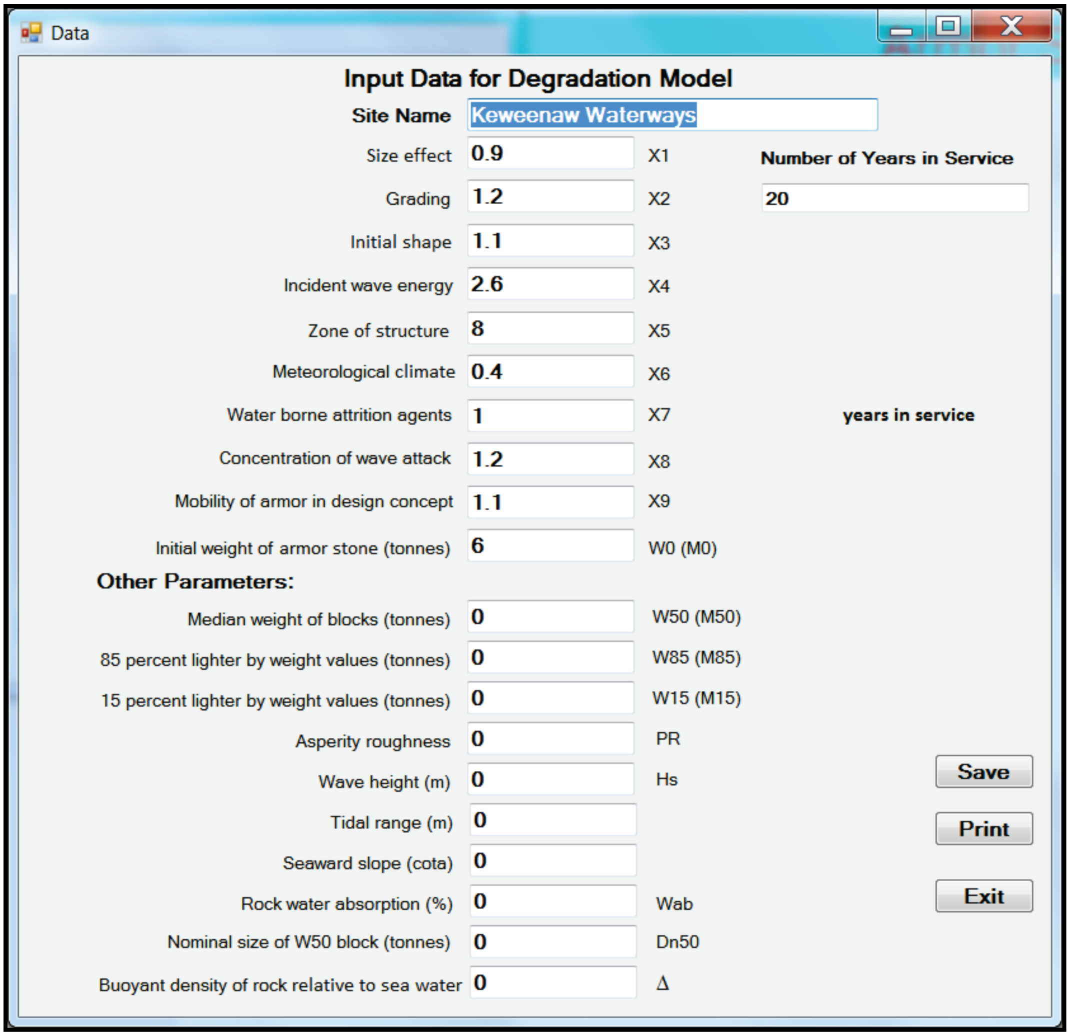
If *Degradation Rate* is selected, a window such as Figure 9 opens.

Figure 9. Existing input data files for degradation rate model.



The user selects a site from the list; for example, *Keweenaw Waterways.inp*, and clicks *Open*. A window such as that shown in Figure 10 opens.

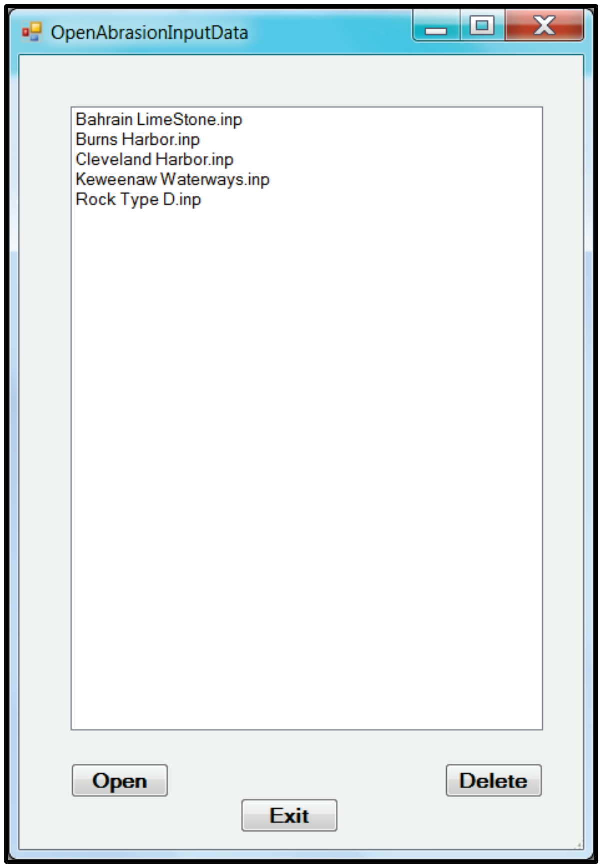
Figure 10. Input data for degradation rate model.



The data in Figure 10 are described in Chapter 2 (Theory) of this document. The data on this form can be changed by the user. After checking the input data, the user may click the *Save* button and go to the menu bar options. For this model, abrasion data must be selected from *Mill Abrasion Data, Input Data*. The user must be sure the name of the degradation rate input file is the same as that in the *Mill Abrasion Data, Input Data* file. For example, using the above Figure 10, the file name for both *Model Input Data*, *Degradation Rate* and *Mill Abrasion Data, Input Data* (*Existing Input)* is Keweenaw Waterways.inp.

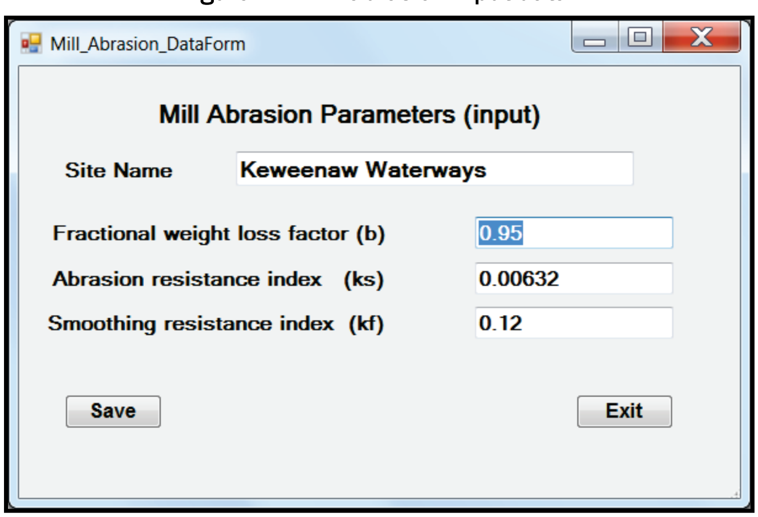
After saving the above data, the user goes to *Mill Abrasion Data, Input Data* (*Existing Input)* and sees the following window (Figure 11).

Figure 11. Available mill abrasion data input files.



From the above list, (using the example) the user should select *Keweenaw Waterways.inp* and click *Open*. The window in Figure 12 will open.

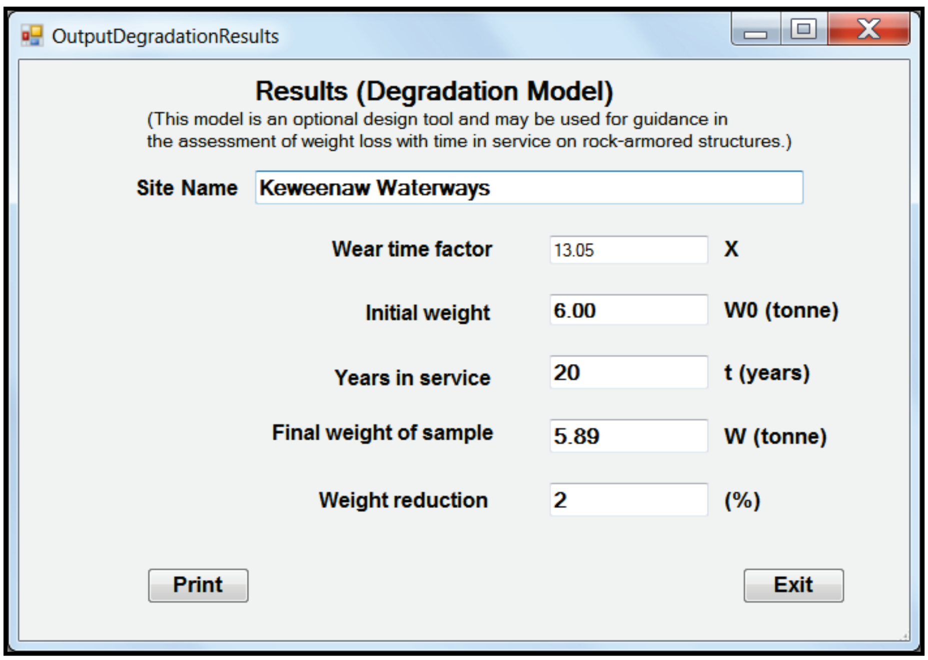
Figure 12. Mill abrasion input data.



From Figure 12, the user may change the data or keep the data unchanged. The user clicks *Save* to save data. After saving the data, the user can view the Mill Abrasion Data graph by going to other options under *Mill Abrasion Data*, *Show Plot,* or *Show Plot in Excel*. For detailed information on the parameters used in Figure 12, the user is referred to Latham and Poole (1988).

After saving the Mill Abrasion Data, the user then can go to *Models* and click *Run Degradation Rate* to simulate the model. Note that Mill Abrasion Data are needed only for this model. After executing the model, the user can then go to *Output***,** *Degradation Output*, and *Open New Output* and see the result, which will be similar to Figure 13.

Figure 13. Results of degradation rate calculations.

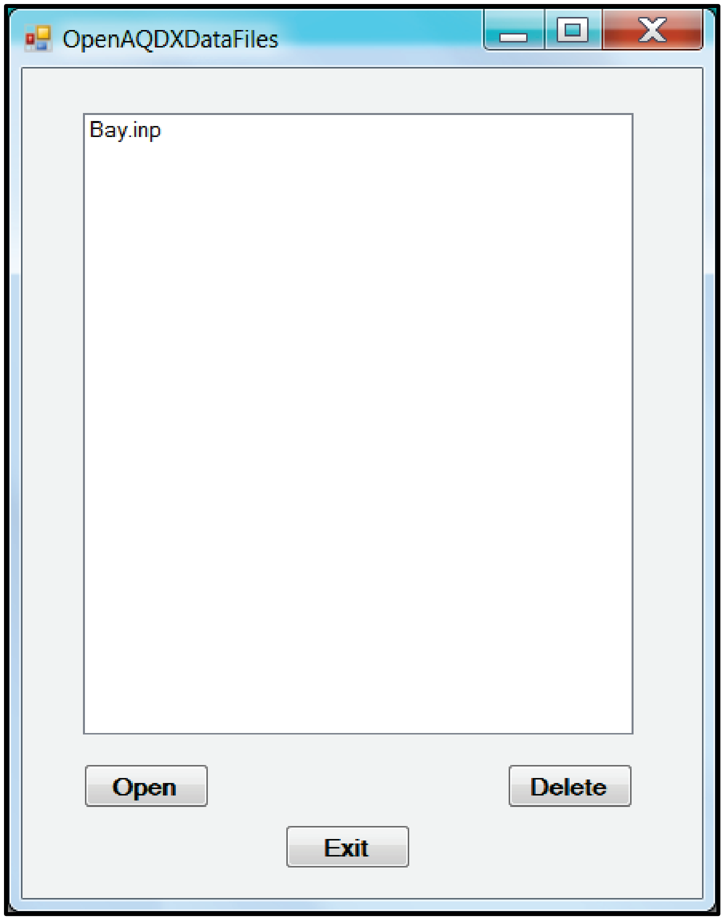


In addition to the above degradation model, the user can utilize another option called *Degradation AQD* in the *Model* option. This selection is an alternative to *Mill Abrasion Data*.

5.3.2 Degradation AQD

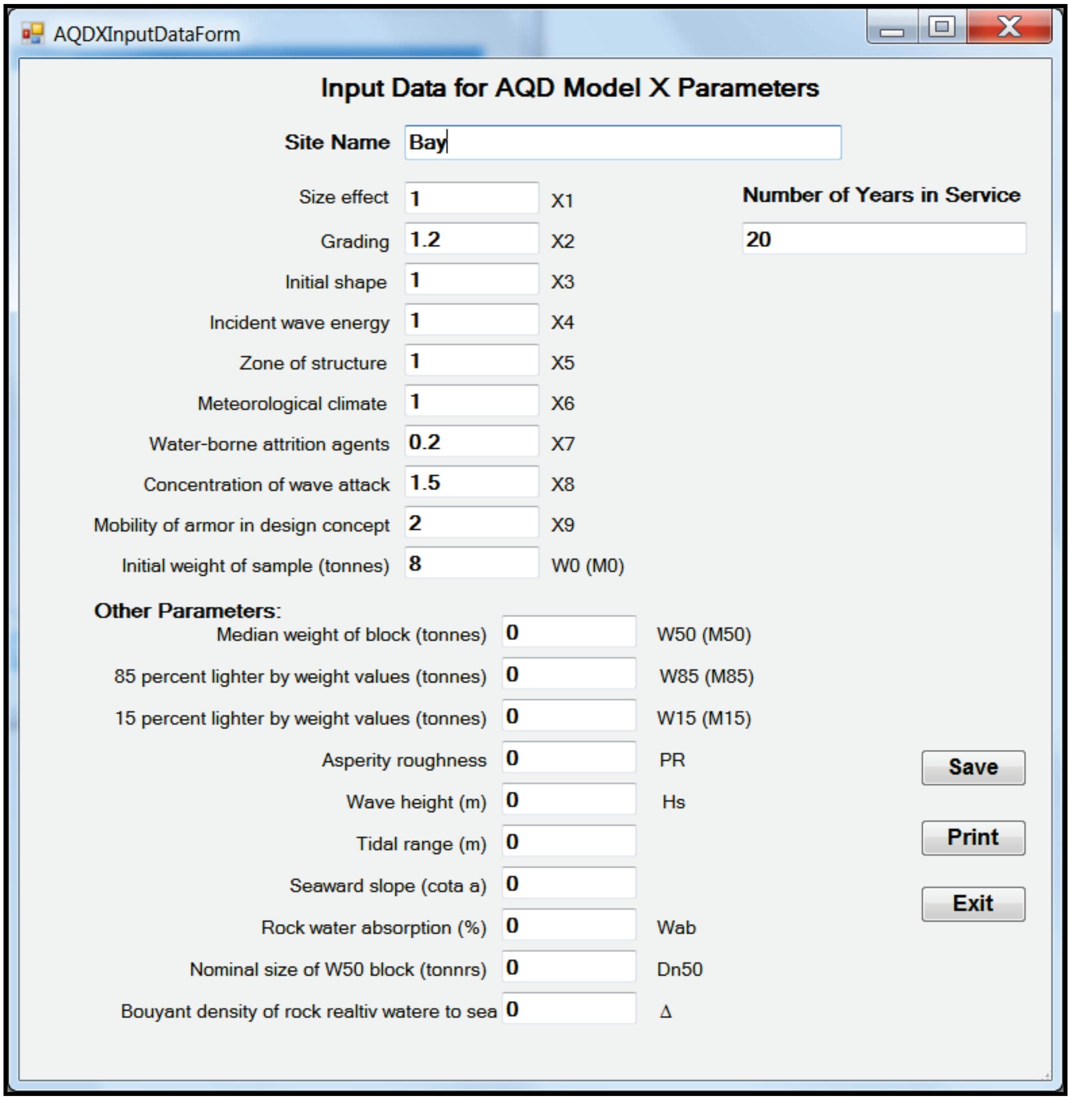
If the user selects *Degradation AQD* under the *Model Input Data*, two sets of data input must be selected: (1) X-Factors, and (2) AQD Worksheet. The user must first select the X-Factors, and a window such as Figure 14 opens.

Figure 14. List of degradation AQD model input data files for x-factors.



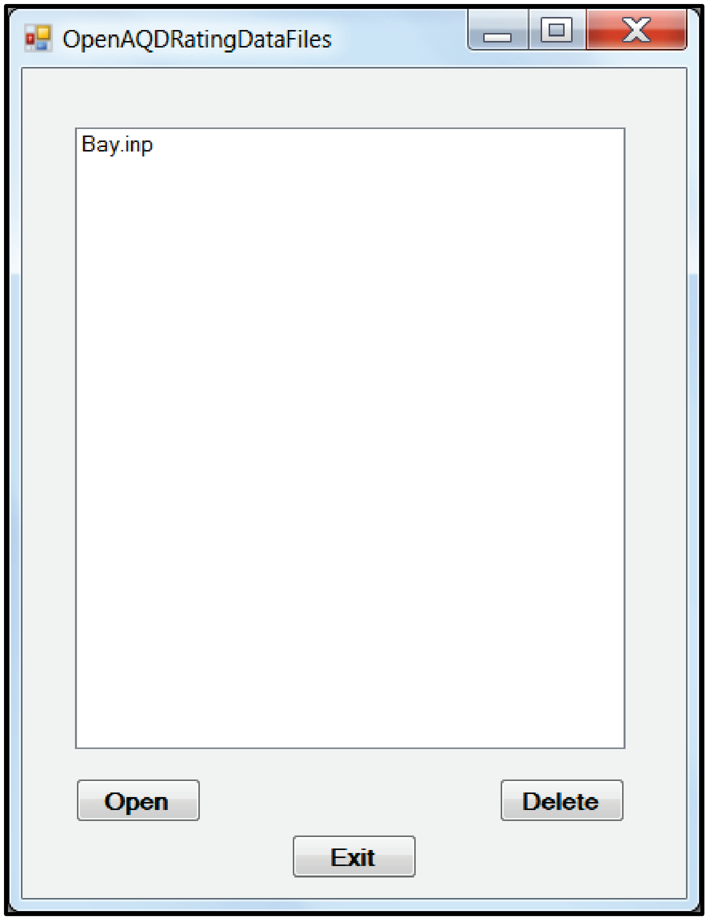
The user then selects a file such as *Bay.inp* in Figure 14 and clicks *Open*. At this point a window such as Figure 15 opens.

Figure 15. Input data for degradation AQD model calculations for x-factors.



After saving the above data by clicking the *Save* button, the user's next step is to select *AQD Worksheet* data. To do this, the user goes to *Model Input Data* and selects *Degradation AQD* and *AQD Worksheet*, and a window such as Figure 16 opens.

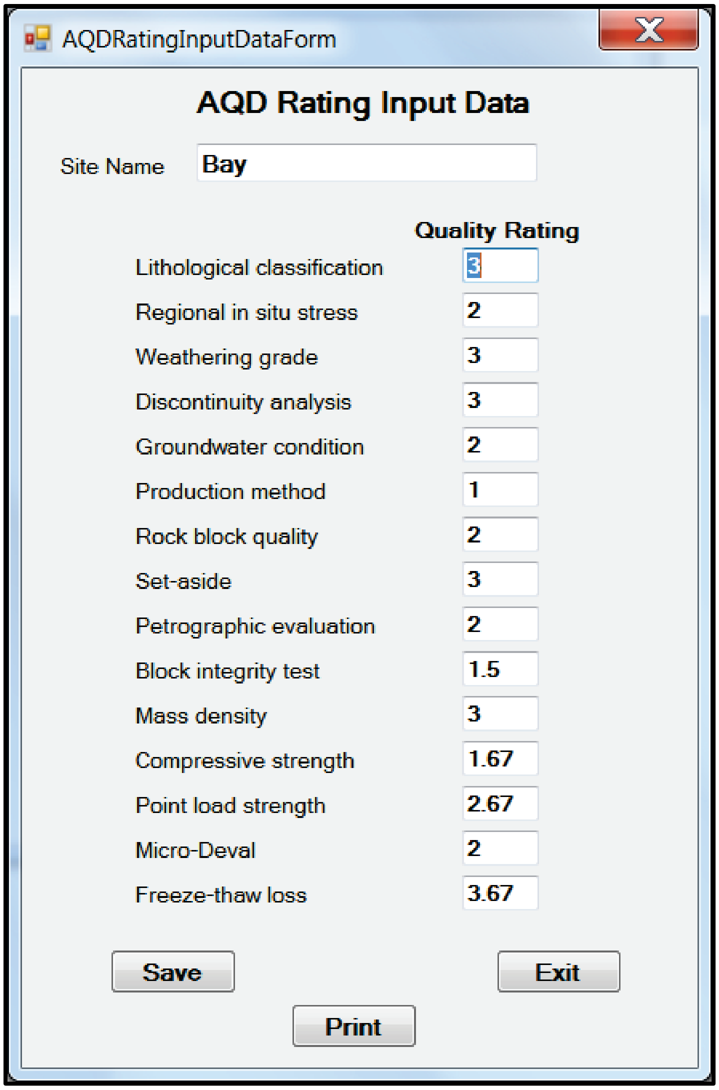
Figure 16. Input files for AQD worksheet rating data.



Select *Bay.inp* and click the *Open* button. A window such as Figure 17 opens.

The sequence of data selection is important. First, the user selects *AQD X-Factors,* and then selects *AQD Worksheet* data. When the user opens the window for *AQD Rating Input Data*, a table will appear on the screen to provide general guidelines for the input parameters.

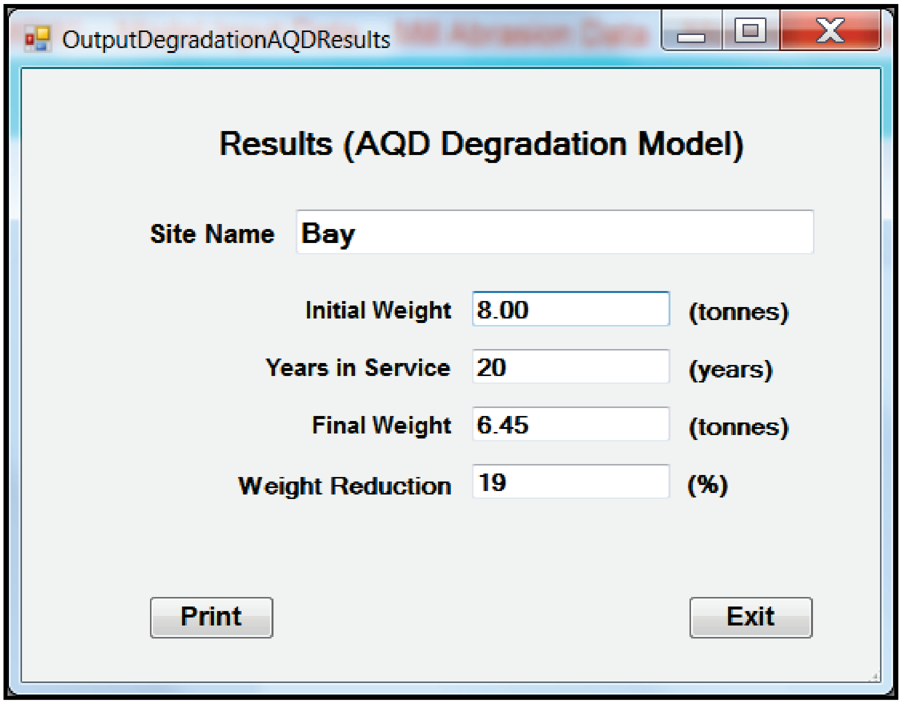
Figure 17. Degradation AQD rating input data.



To run this input file (*Bay.inp*), the user clicks *Save* and then clicks *Exit* and goes to *Models* (only *Run Degradation AQD* is active). Click on this option to run the model. The user now can go to *Model Output Results, Degradation AQD Output,* and *Open New Output* and see the results as shown in Figure 18.

The above Figure 18 shows that an armor stone at a location called Bay initially weighed 8 tonnes and, after 20 years in service, has a 19% reduction weight with a final weight of 6.45 tonnes. The user can print this output to a local (Default) printer or exit the output page.

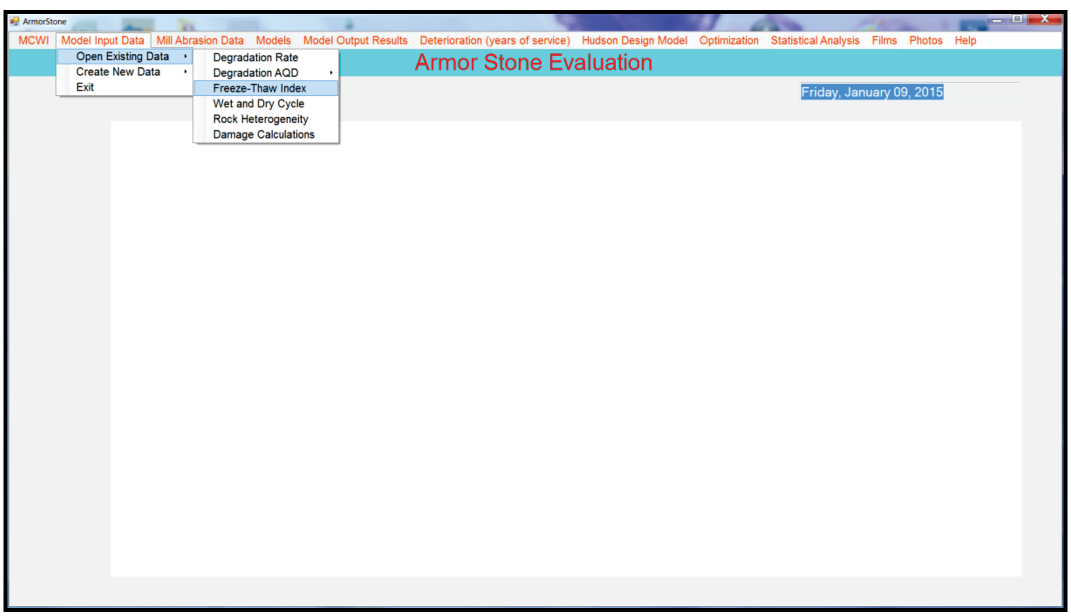
Figure 18. Output of degradation AQD model.



5.3.3 Freeze-thaw index model

Another model option is to estimate the Freeze-Thaw Index (cycle). The first step is to select or create a data input as shown in Figure 19.

Figure 19. Selecting freeze-thaw index (cycle) model.



After clicking *Freeze-Thaw Index* in Figure 19, the following window will open (Figure 20).

Figure 20. Available input files for freeze-thaw index (cycle) calculation.

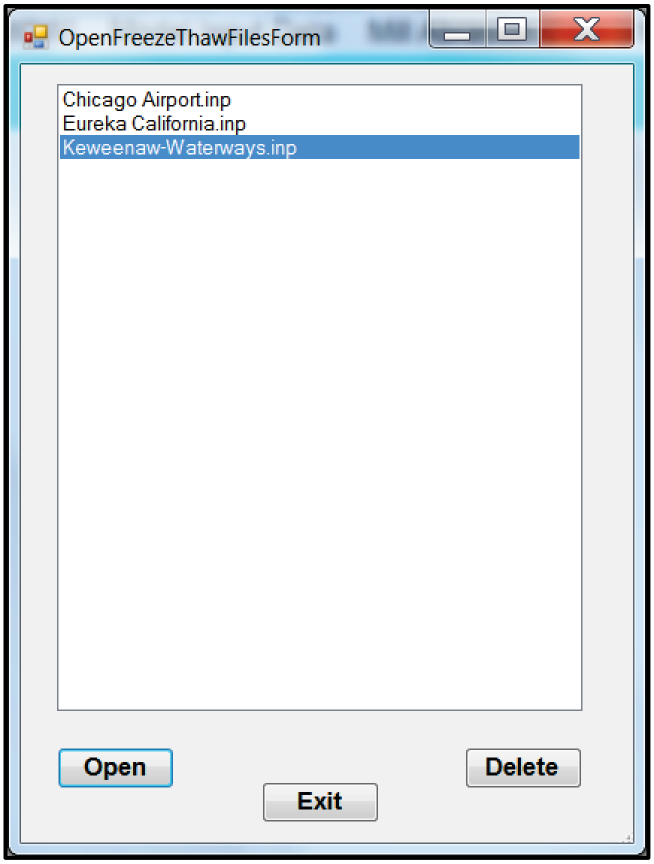


Figure 20 shows three files are available for Freeze-Thaw Index (cycle) calculations. Each time the user creates a new file, it will be saved in this list. The user has the option to delete files that are not needed (Delete Button in Figure 20).

In this example, *Keweenaw-Waterways.inp* was selected as the input file. By clicking *Open*, a window such as the following opens (Figure 21).

Figure 21. Data for calculation of freeze-thaw index (cycle).

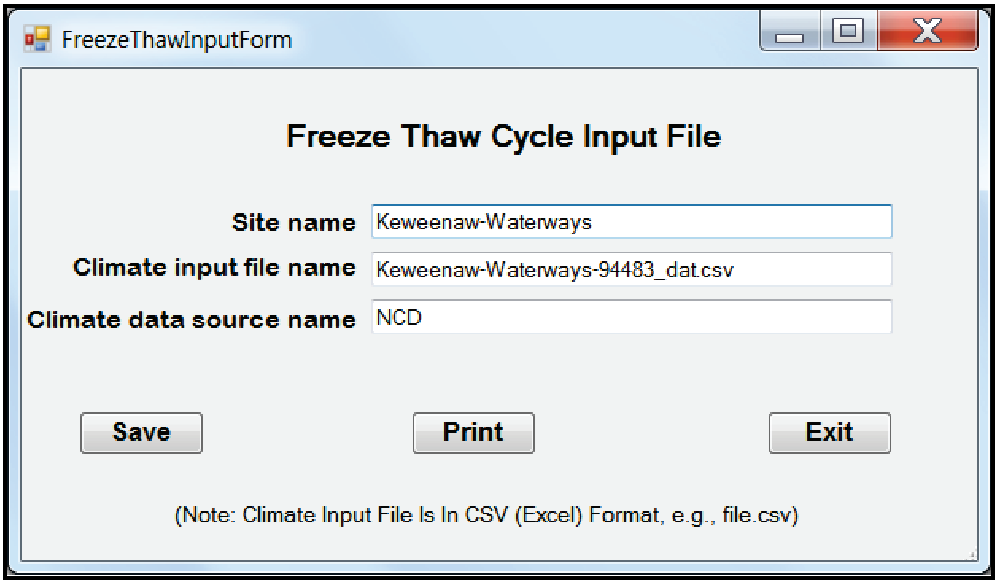


Figure 21 requires three input parameters: (1) *Site Name* (here, Keweenaw-Waterways), (2) *Climate Input File Name* (here, Keweenaw-Waterways-94483_dat.csv), and (3) *Climate Data Source Name* (here, the NOAA NCDC is used as the data source).

The climate data (Keweenaw-Waterways-94483_dat.csv) was downloaded from the NOAA NCDC web site, and must be formatted according to instructions provided in this user's manual. After opening the above window, the user clicks the *Save* button to save the data.

The next step is to run the Freeze-Thaw Intensity model as shown in Figure 22. The user has two options: (1) Lienhart's technique, or (2) Arnold's technique. The differences of these two techniques are described in Chapter 2 of this user's manual.

After running the model, the user can open the output as shown in Figure 23.

Figure 22. Selecting and running freeze-thaw intensity model.

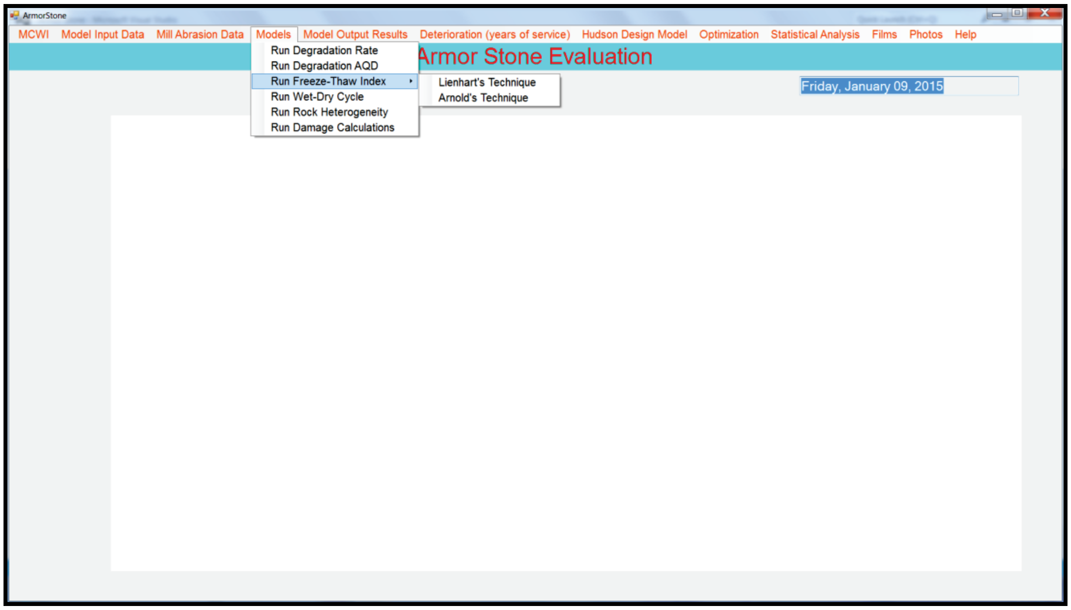
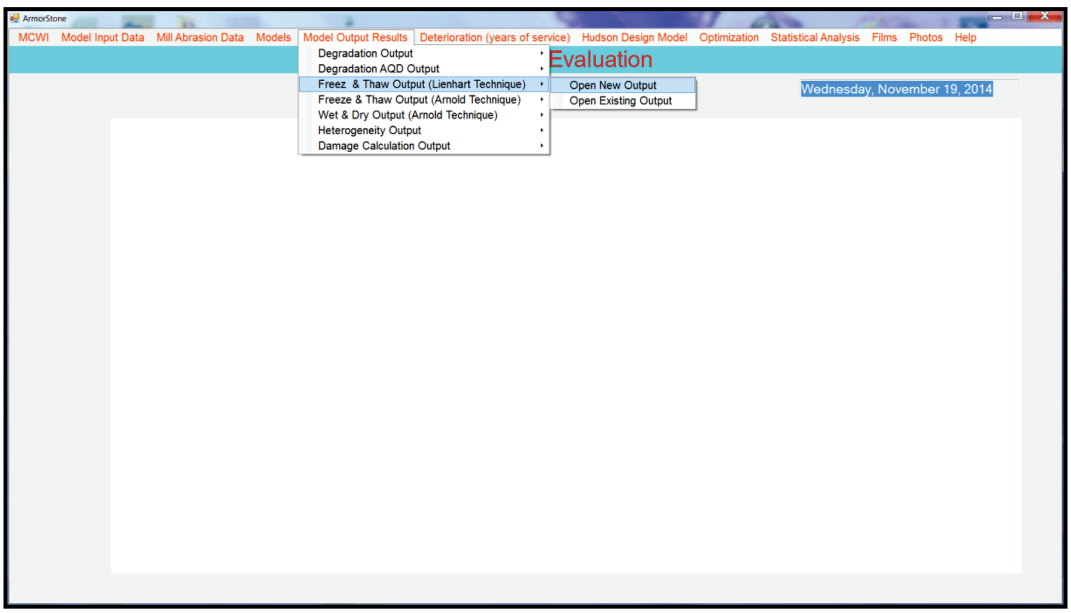


Figure 23. Opening output from freeze-thaw intensity model using Lienhart's technique.



In this example, *Lienhart's Technique* was selected, and the new output is shown in Figure 24.

Figure 24. New output for freeze-thaw index calculation for Keweenaw Waterways using Lienhart's technique.

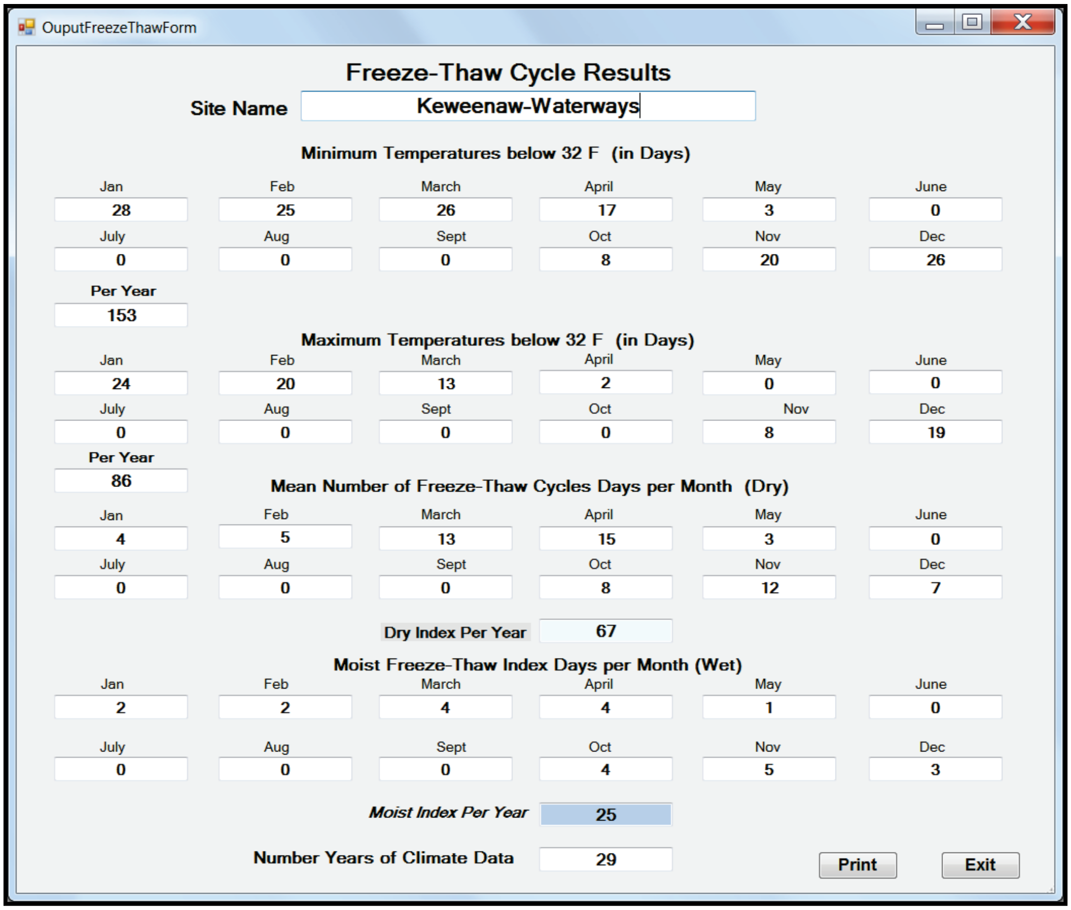
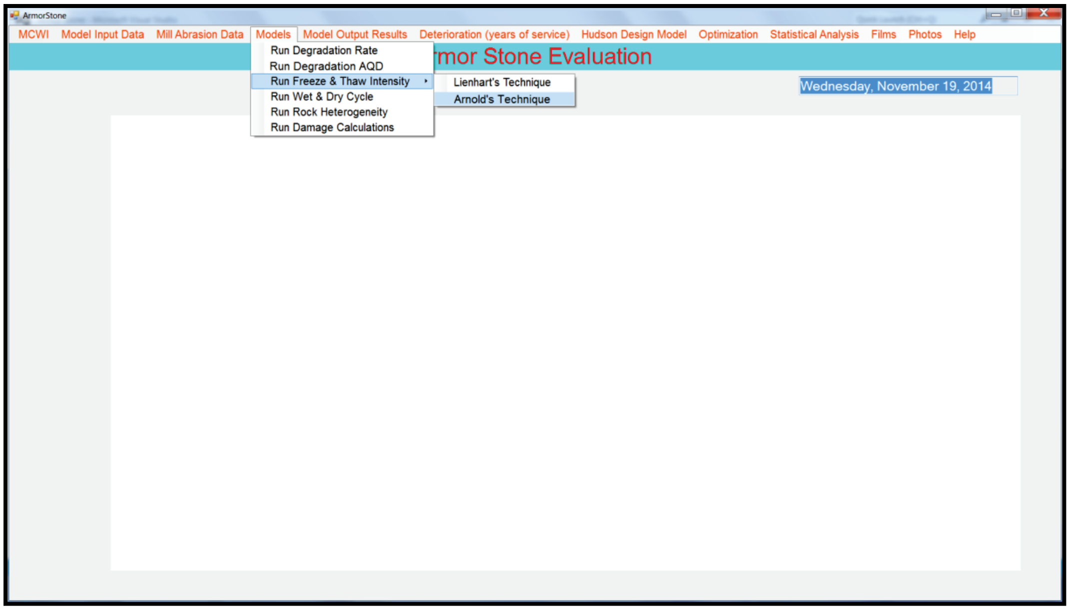


Figure 24 shows new output for the selected site in this example. The index is calculated from 29 years of climate data with a Dry Index per Year of 67 and a Moist Index per Year of 25.

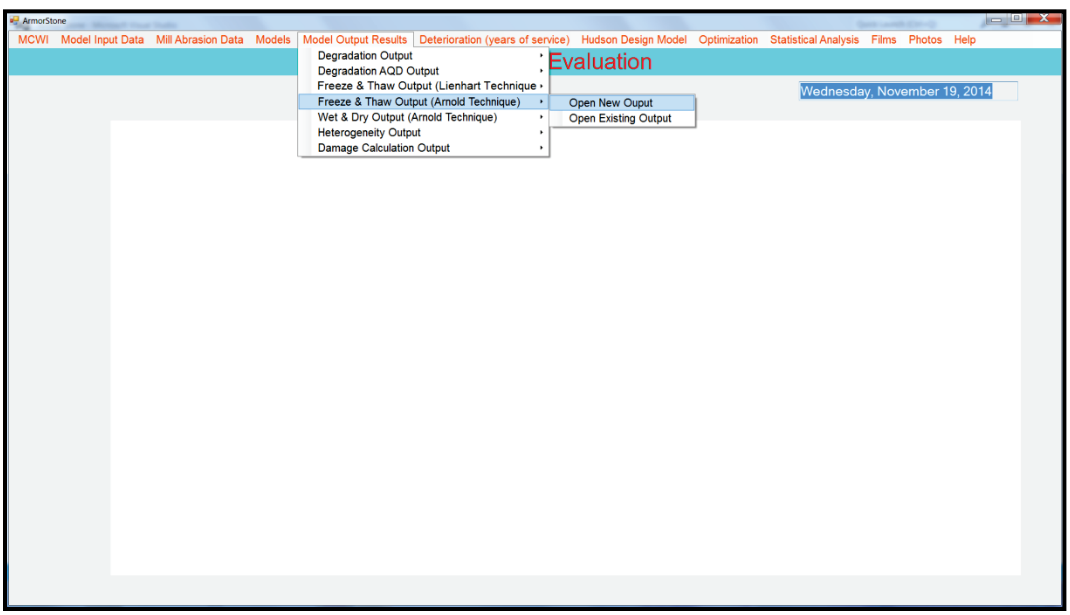
The second option for calculation of the freeze-thaw cycle is based on Arnold et al. (1996). The user selects the input file as described above. Then, the user selects from *Models, Run Freeze-Thaw Intensity,* and *Arnold's Technique,* as shown in Figure 25.

Figure 25. Opening, selecting, and running freeze-thaw intensity model for Arnold's technique.



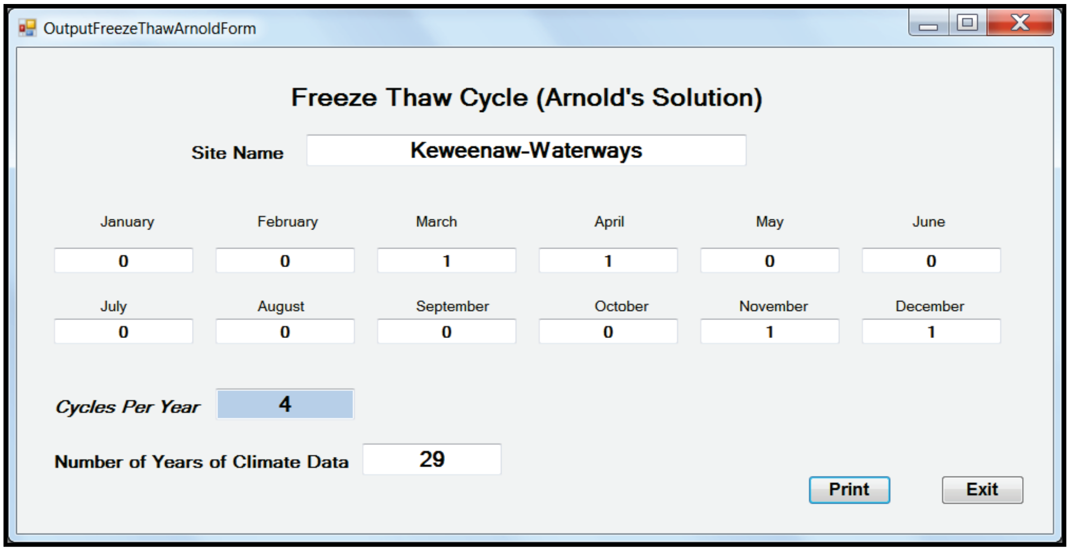
After running the model, the output can be selected from the *Model Output Results* as shown below in Figure 26 below.

Figure 26. Opening new output for freeze-thaw intensity model using Arnold's technique.



The example output for *Arnold's Technique* is shown in Figure 27.

Figure 27. Example output for freeze-thaw intensity model for Keweenaw Waterways using Arnold's technique.



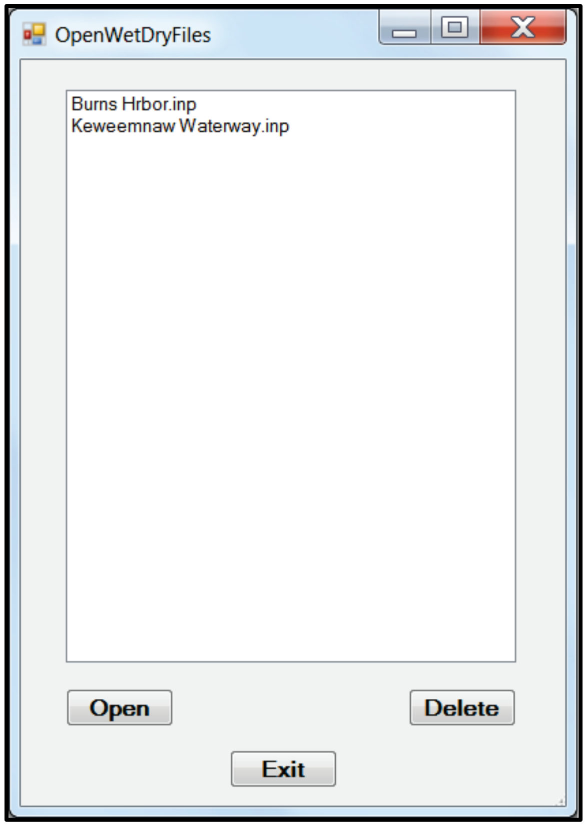
5.3.4 Wet and Dry Cycle

To calculate the wet and dry cycle, the user can either create a new input file, or select an existing input file as described and shown here. First, the user selects *Model Input Data, Open Existing Data,* and *Wet and Dry Cycle,* as shown in Figure 28.

Figure 28. Selecting and opening existing input file for wet and dry cycle model.

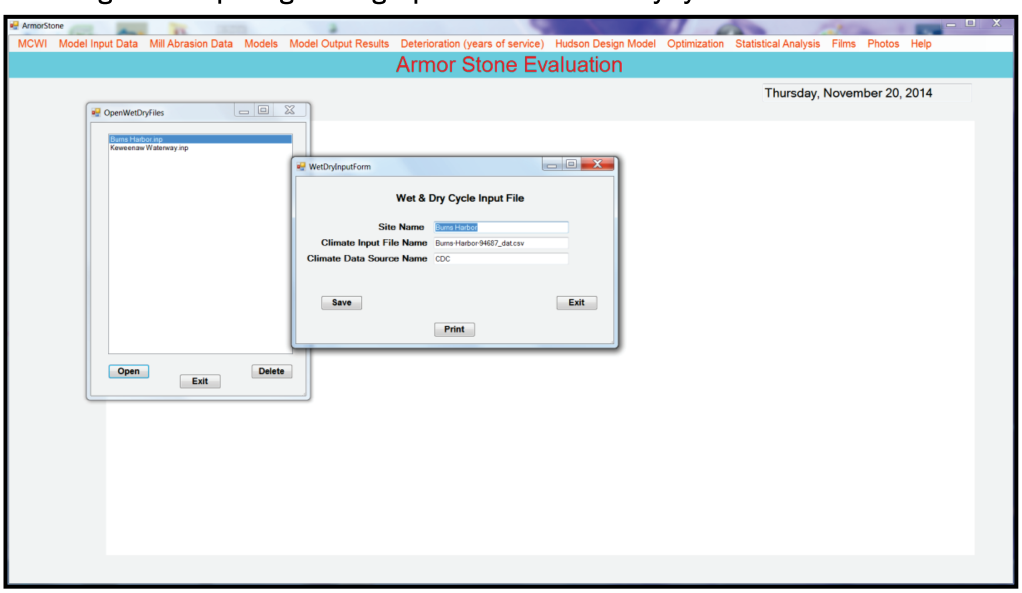
As a result of this action, the window of Figure 29 will open to show a list of existing input data files.

Figure 29. Existing input files for wet and dry cycle model.



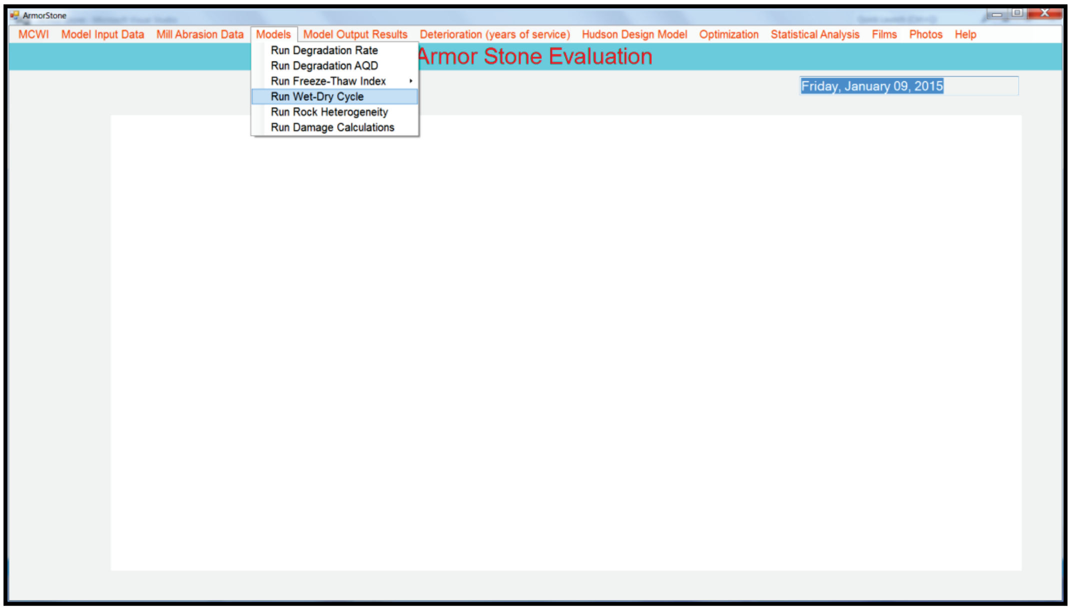
From the above list, as an example, the user selects *Burns Harbor.inp* by clicking the file name. The user then clicks the *Open* button to open the file as shown in Figure 30.

Figure 30. Opening existing input file for wet and dry cycle model calculation.



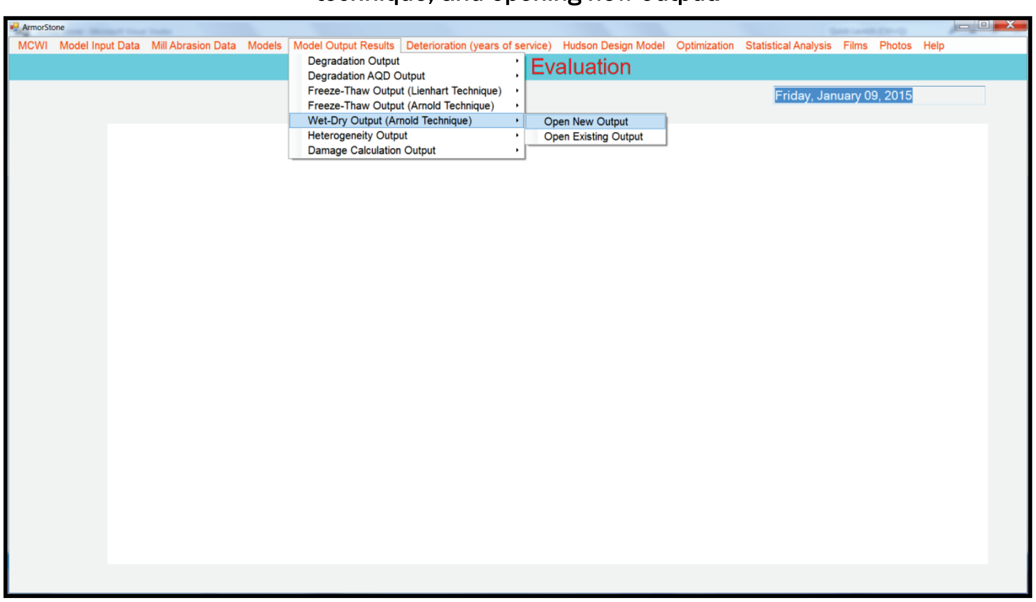
The user should click the *Save* button on the window for *Wet and Dry Cycle Input File* and save the file. The next step is to run the wet and dry cycle model by selecting *Models,* and *Run Wet and Dry Cycle* as shown below in Figure 31.

Figure 31. Selecting and running wet and dry cycle model.



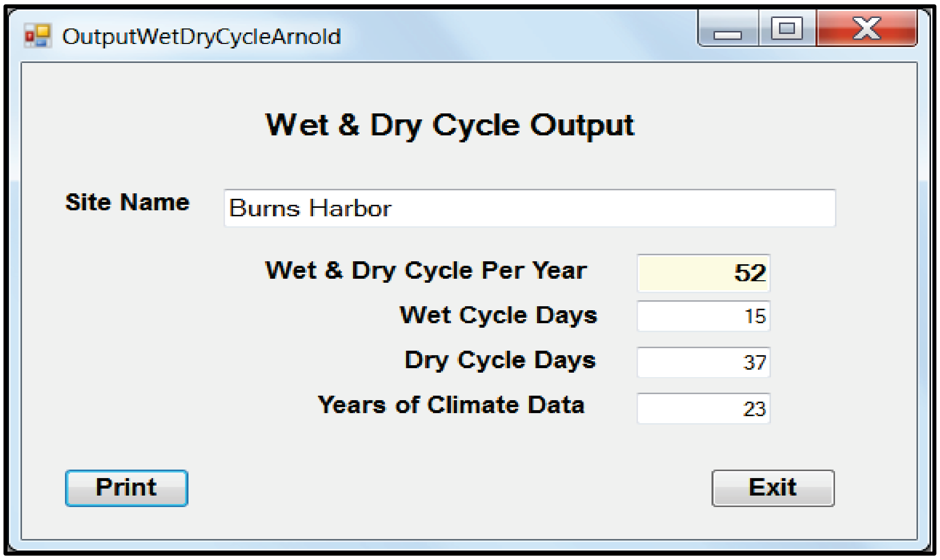
After running the model, the user can see the output from *Model Output Results, Wet and Dry Output (Arnold Technique), Open New Output* as shown below in Figure 32.

Figure 32. Selecting model output results from wet and dry cycle model using Arnold's technique, and opening new output.



The output will look like Figure 33.

Figure 33. Output for wet and dry cycle model for Burns Harbor using Arnold's technique.

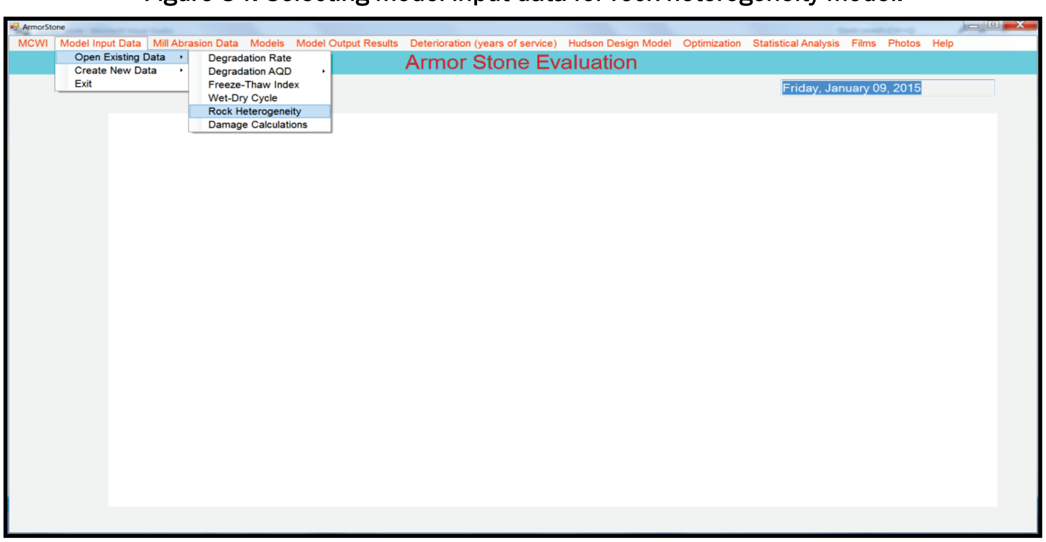


The above window shows the name of the site (Site Name), the total number of wet and dry cycles per year, only wet cycles, only dry cycles, and the total number of years of climate data used for the calculation.

5.3.5 Rock heterogeneity model

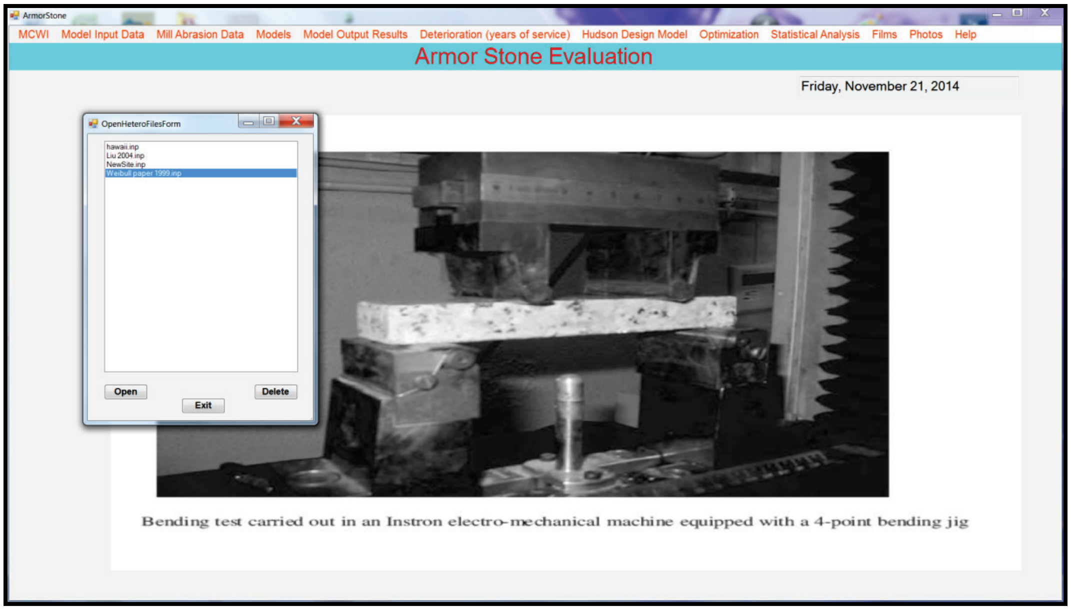
To run the rock heterogeneity model, the user selects or opens the existing input file as shown in Figure 34, *Model Input Data, Open Exiting Data,* and *Rock Heterogeneity*.

Figure 34. Selecting model input data for rock heterogeneity model.



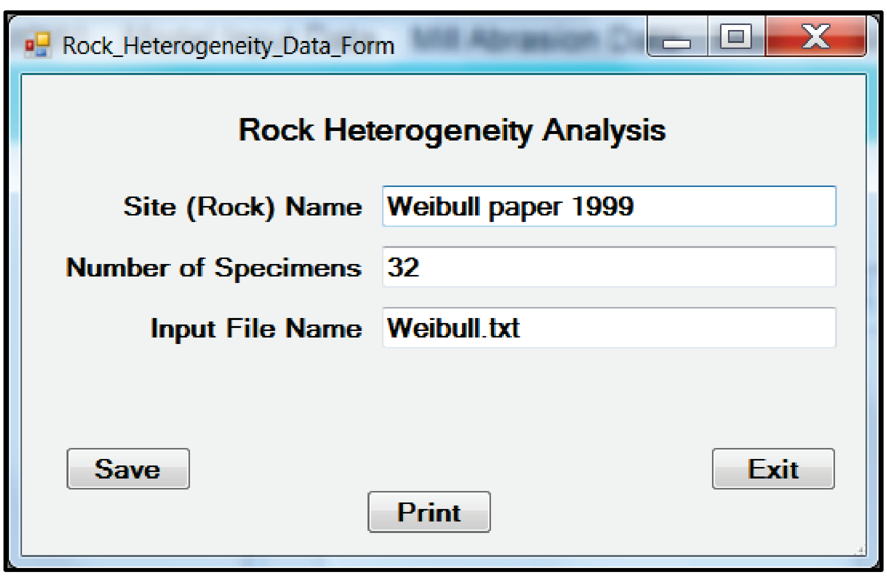
By clicking *Rock Heterogeneity* (shown above), the user opens a window such as that in Figure 35.

Figure 35. Opening window for list of existing rock heterogeneity input files.



From the list of files shown on the open window above, the user may select *Weibull paper 1999.inp*. Then, the user clicks the *Open* button to see the window in Figure 36.

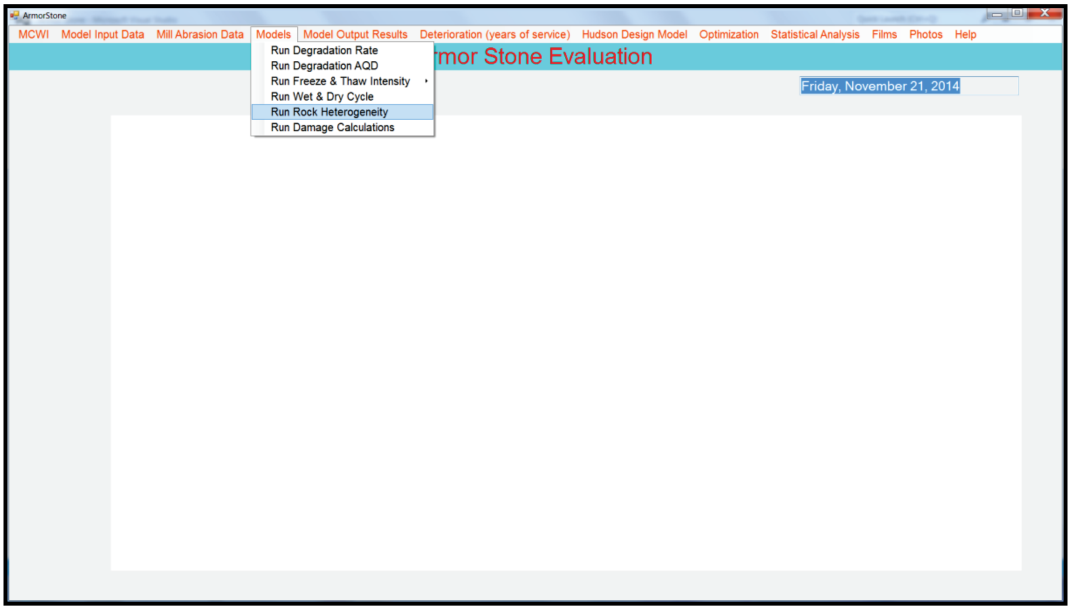
Figure 36. Input file information for calculating rock heterogeneity.



In Figure 36, Site (Rock) Name is *Weibull paper 1999*, the Number of Specimens used for this test is 32 (see Theory Chapter for more information), and the input text file that has actual data is called *Weibull.txt*. The *Weibull.txt* file should be located in *Armor-Stone, Bin, Debug* directory.

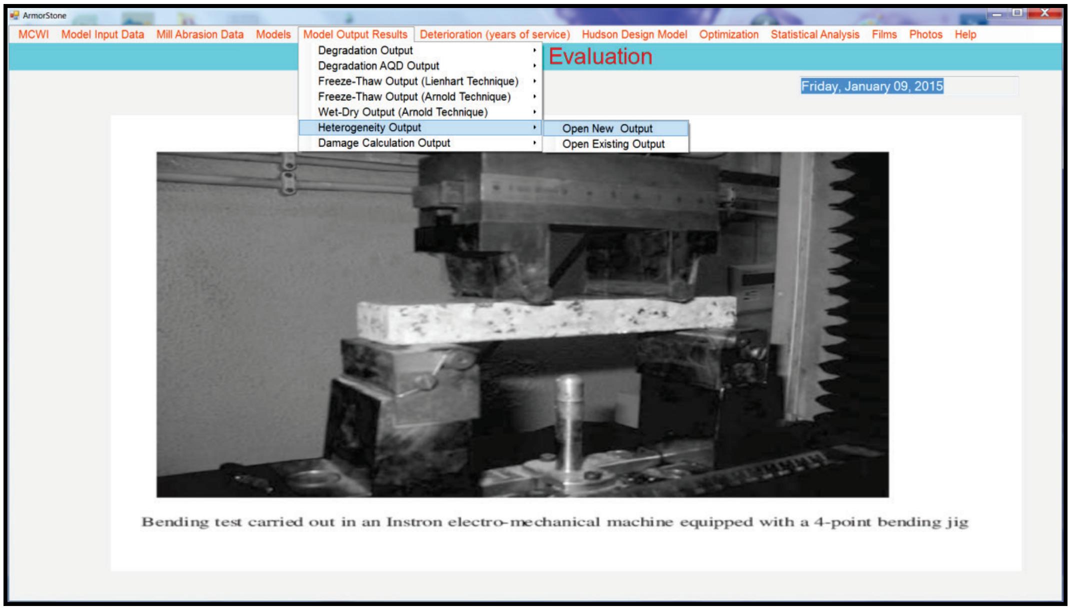
To save the input file, the user should click the *Save* button in the window above. The next step is to run the model. The user goes to *Models,* and *Run Rock Heterogeneity* as shown in Figure 37.

Figure 37. Selecting and running rock heterogeneity model.



After clicking the *Run Rock Heterogeneity* model, the user can then select the new output as shown below in Figure 38.

Figure 38. Selecting new output windows for rock heterogeneity model.



The results from the model output will open as shown in Figure 39.

Figure 39. Results from running rock heterogeneity model.

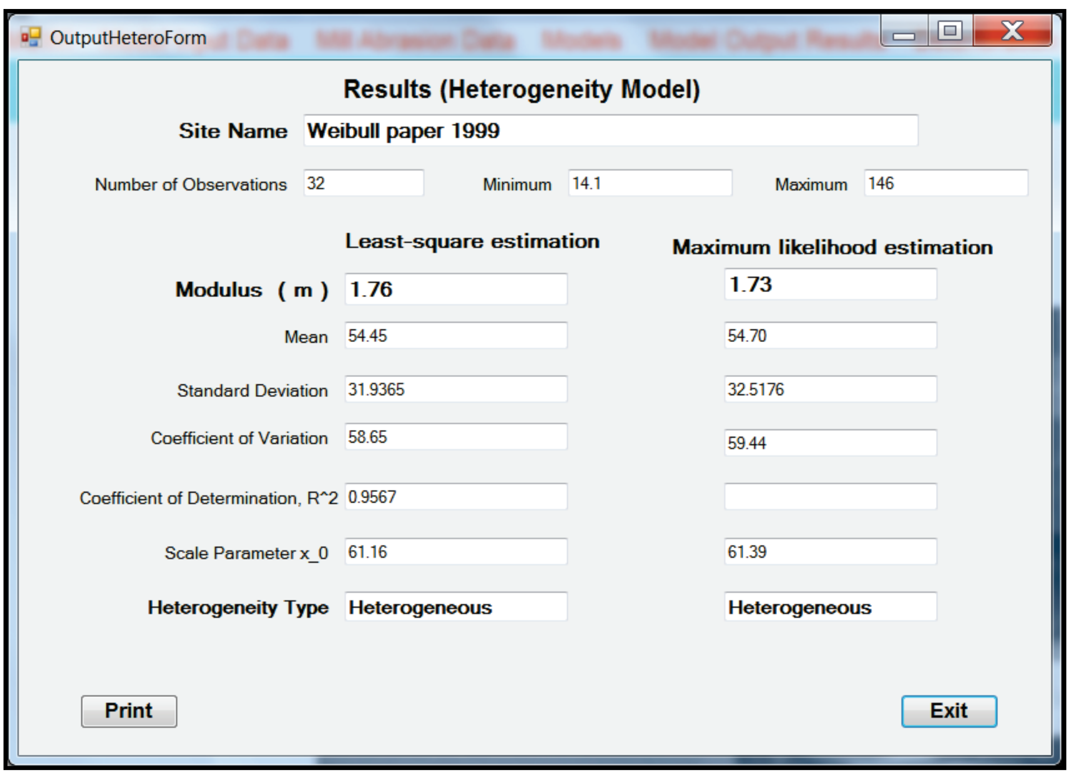
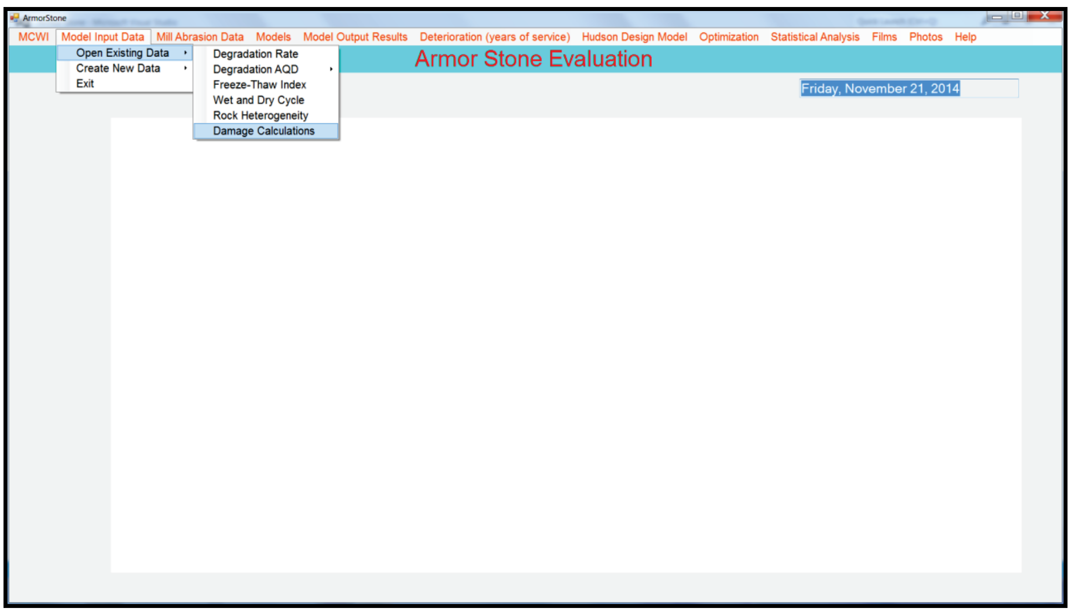


Figure 39 provides input and output data for this selected site. The total number of data points was 32, the minimum value was 14.1, and the maximum value was 146. The border between heterogeneity and homogeneity for this technique needs to be explored. At present, it is assumed that a modulus, *m*, less than 5 indicates the sample rock is heterogeneous, and *m* greater than 5 indicates the sample rock is homogenous. In the above example, the modulus, m, is 1.76 which is less than 5. Therefore, the rock sample is assumed to be heterogeneous.

5.3.6 Damage calculations

Damage estimation of armor stone was described in Chapter 4. The user can select *Open Existing Data* for this calculation. The screen would look like Figure 40.

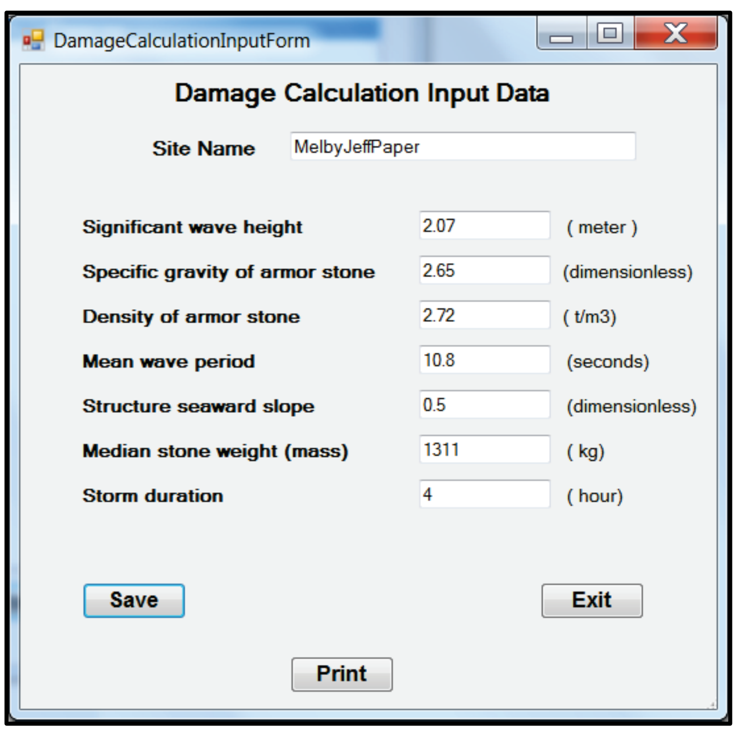
Figure 40. Selecting existing data file for armor stone damage calculations.



By clicking *Damage Calculations,* as shown in Figure 40, a window will open as shown in Figure 41. This window shows a list of existing data files. For this example in Figure 41, only one file exists with the name of *MelbyJeffPaper.inp*. The user can select the file and click the *Open* button to open the data file, as shown in Figure 42.

Figure 41. Existing input files for damage calculations model.

Figure 42. Data values for example used in the damage calculations.



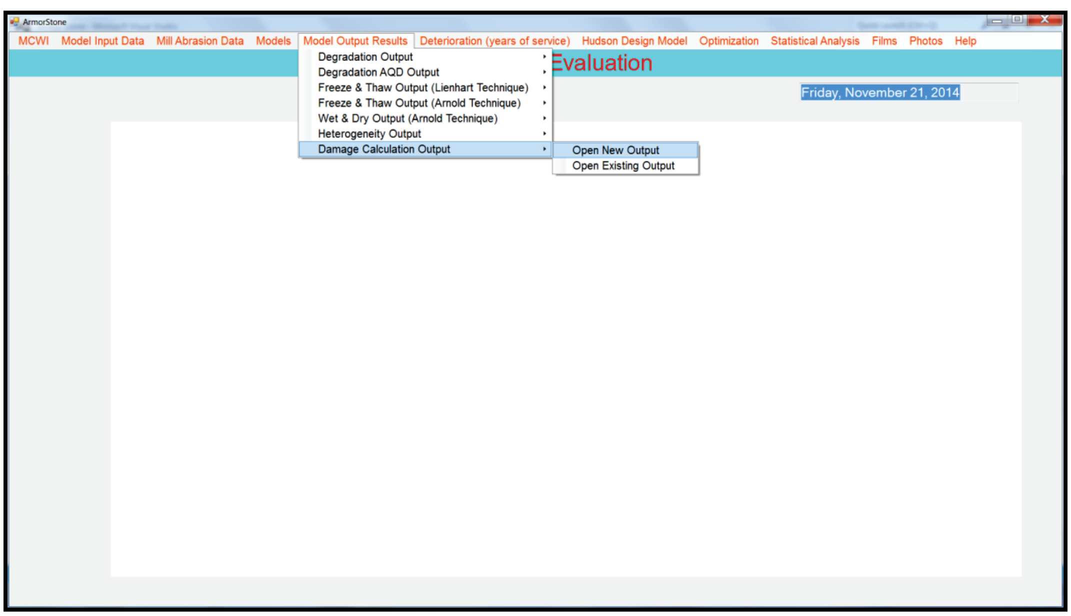
After opening the data set shown in Figure 42, the user should click the *Save* button to save the data and then click *Exit*.

The next step is to run the model as shown in Figure 43 by selecting *Run Damage Calculations* from the list of models provided in the options of *Models*.

Figure 43. Selecting and running the damage calculations model.

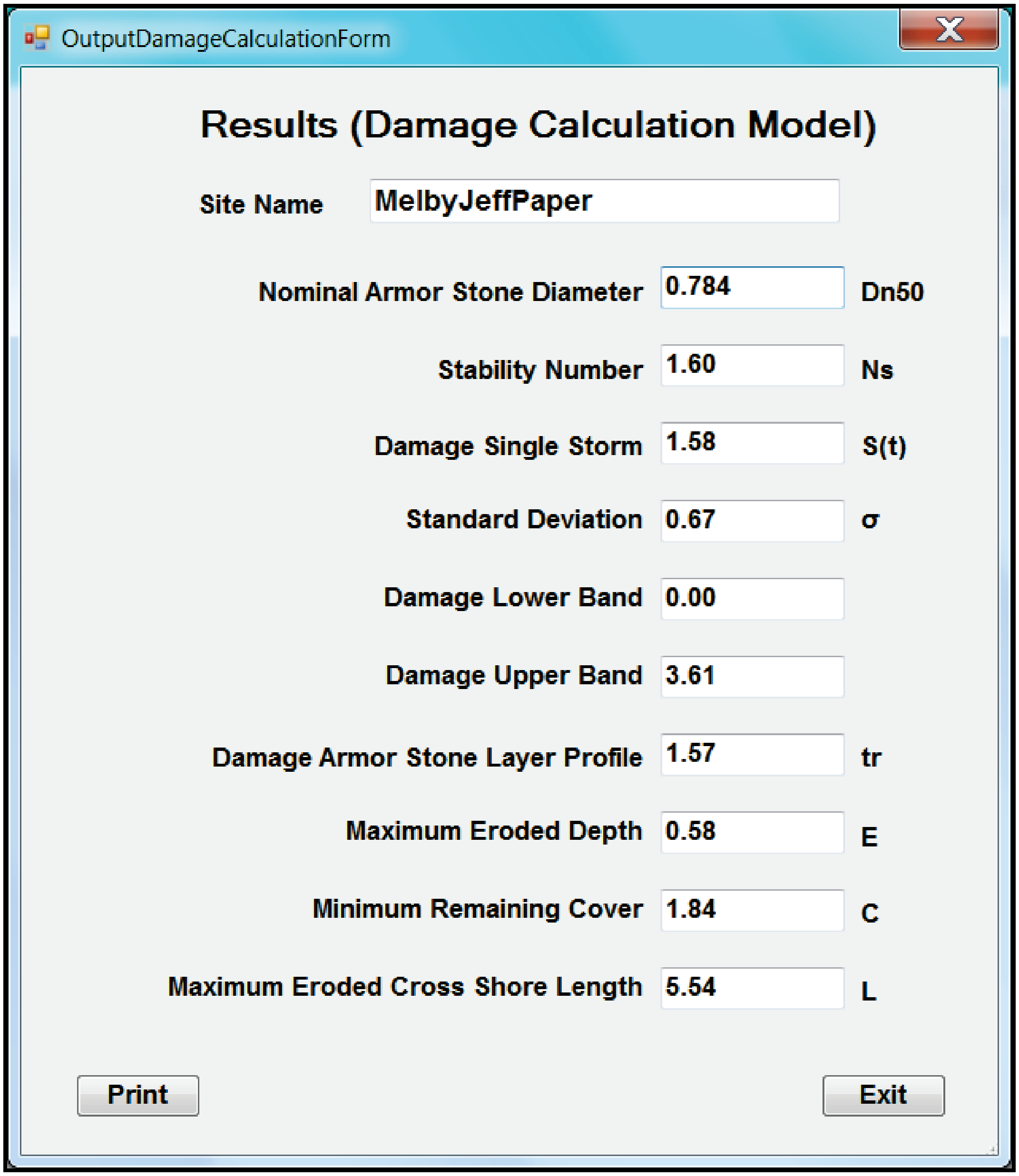
The next step is to select and see the output as shown in Figure 44.

Figure 44. Selecting output for the damage calculations model.



As shown in Figure 44, click *Open New Output*. A window will open with output data as in Figure 45.

Figure 45. Results of the damage calculations model.



The user can either exit the output or print it on the default printer. For more information about the damage calculation input data of Figure 42 used to generate Figure 45, the user is referred to Chapter 2 of this document.

6 Summary and conclusions

6.1 Summary

Protecting entrances to navigation channels, harbors, or other coastal areas requires evaluating maritime structures that are often constructed with a surface layer of armor stones, such as rubble-mound breakwaters and jetties. Armor rocks are impacted by the natural deteriorating elements such as seasonal weather and repeated cycles of temperature, flowing water, wetting and drying, wave action, and freeze and thaw. The design process for the determination of armor stone sizes is complex, and various factors must be considered to fully understand how design parameters affect the stone's performance.

The outer layer of a rubble-mound coastal structure is presently designed for stability based on the dominant wave climate and tidal range anticipated over the desired life of the structure at that specific site, and on the specific gravity and quality of the available stone that will comprise the armor layer. It is inherently presumed that the same stone size will still exist at the end of the desired time period, without degradation in size due to weathering effects caused by freeze-thaw cycles, wet-dry cycles, and ice scour. At structure sites in severe climatic conditions, it is realized that armor stone degrades in size over time, losing some of its capacity to resist the wave climate for which it was designed.

The purpose of this USACE MCNP study was to evaluate and quantify major factors affecting armor stone durability. Field monitoring and laboratory testing were conducted to evaluate the performance of stone subjected to both freezing-thawing and wetting-drying, and to quantify the combined effects of environmental stresses on armor stones. In addition, long-term performance or deterioration of armor stones has been quantitatively monitored and characterized by changes in measured dimensions.

6.2 Conclusions

As part of the study, Armor Stone Evaluation (ARMOR) software was developed that integrates field observations with numerical tools to provide an assessment of the local freeze-thaw and wet-dry cycles on the

stones. The ARMOR software has several numerical models that predict degradation of armor stone as the rocks are impacted by natural elements. The software includes a statistical technique (homogeneity index) to characterize rock heterogeneity. Two new numerical approaches have been developed to calculate freeze-thaw cycles using long-term site weather data. The software also provides a model to estimate armor weight, minimum crest width, armor thickness, and number of armor units per unit of area. The calculation uses varying values for the seaward slope and wave height by application of the Hudson (1958) formula for rubble-mound structure stability. The degradation model relates the laboratory test results to the modification of the mass distribution and reduction at the project site.

ARMOR has been developed to ascertain the amount of degradation the stones will experience over time for given climatic conditions and stone type. Thus, ARMOR can be used as an optimizing tool to determine how oversized an armor stone should initially be to still provide the desired level of protection after the design life of the structure has passed. Alternatively, stone of different characteristics may be available but at vastly different unit prices with the better quality stone costing much more than a lesser quality stone. In such a case, ARMOR can be used to optimize the life-cycle cost of the structure by determining how much larger a less expensive but lesser-quality stone would need to be for the design life of the structure, compared to a smaller but better-quality stone at a much higher unit price.

The user should have a technical background with some knowledge of coastal or hydraulic engineering. ARMOR requires a minimum of 900 megabytes (MB) of hard disk space and two gigabytes (GB) of random access memory (RAM). This document provides step-by-step instructions for creating input data and running different options of the program. Chapter 2 of this document provides theoretical formulations used for each of the models within ARMOR.

ARMOR software was developed for personal computers (PC), either desktop or laptop client-based applications. Thus, the entire program and files reside on the user's PC.

ARMOR software is currently distributed by CD or DVD. A copy may be obtained from Dr. Mansour Zakikhani, U.S. Army Engineer Research and Development Center, Environmental Laboratory, 3909 Halls Ferry Road, Vicksburg, MS, 39180; (Mansour.zakikhani@usace.army.mil); phone 601-634-3806.

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Mansour Zakikhani, Danny W. Harrelson, Amber L. Tillotson, and John D. Ables

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14. ABSTRACT
Protecting entrances to navigation channels or other coastal areas requires evaluating maritime structures that often feature a surface layer of armor stones, such as rubble-mound breakwaters and jetties. Armor rocks are impacted by natural elements such as seasonal weather and repeated cycles of temperature, flowing water, wetting and drying, wave action, and freeze and thaw. The Armor Stone Evaluation (ARMOR) numerical simulation model consists of stone deterioration software developed to integrate field observations with numerical tools, and it provides an assessment of stone performance during the life of the rubble-mound structures. The ARMOR software has several numerical models that predict degradation as rocks are impacted by nature. The software includes a statistical technique (homogeneity index) to characterize rock heterogeneity. Two numerical approaches have been developed to calculate freeze-thaw cycles using long-term site weather data. The software also provides a model to estimate armor weight and thickness, minimum crest width, and number of armor units per unit of area. The calculation uses varying values for the seaward slope and wave height by application of the Hudson formula for rubble-mound structure stability. The degradation model relates laboratory results to modification of mass distribution and reduction at the project site. This report provides instructions for creating input data and running different options of the program. ARMOR software is distributed on CD or DVD and may be obtained from Dr. Mansour Zakikhani, U.S. Army Engineer Research and Development Center, Environmental Laboratory, 3909 Halls Ferry Road, Vicksburg, MS, 39180; (Mansour.zakikhani@usace.army.mil); phone 601-634-3806.

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